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**Autopoietic-Extended Architecture:
Can Buildings Think?**

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Autopoietic-Extended Architecture: Can Buildings Think?

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Certification •

I affirm that I am the sole author of "Autopoietic-Extended Architecture: Can Buildings Think?" The writing, research, graphics, photographs, and arguments presented herein are original works in an original synthesis I created and researched during the period of my enrollment as a PhD student at the University of Edinburgh between 2011 and 2014. All references and quotations are cited in the bibliography and, within the text, placed either in quotation marks and/or clearly identified by stand-out paragraphing with authors and identifying years of publication that synchronize with full publication data in the bibliography. Much of the graphic material I have directly created and appropriately credited as part of the thesis research. In cases where graphic material is copyrighted, written permission has been received; this applies to the two paintings owned by the Museum of Modern Art, New York, the four architectural drawings owned by the Chicago Institute of Art, and the five drawings by Turing in the estate of P.N. Furbank. Papers published, submitted, or currently in preparation for journals as part of the PhD process are cited (Appendix 3). Conferences attended where papers were presented are also cited (Appendix 3).

I affirm the above is true and complete.

A handwritten signature in black ink, appearing to read 'Dennis L. Dollens', with a stylized, cursive script.

Dennis L. Dollens

26 July 2014

Abstract •

Autopoietic-Extended Architecture: Can Buildings Think?

To incorporate bioremedial functions into the performance of buildings and to balance generative architecture's dominant focus on computational programming and digital fabrication, this thesis first hybridizes theories of autopoiesis into extended cognition in order to research biological domains that include synthetic biology and biocomputation. Under the rubric of living technology I survey multidisciplinary fields to gather perspective for student design of bioremedial and/or metabolic components in generative architecture where *generative* not only denotes the use of computation but also includes biochemical, biomechanical, and metabolic functions.

I trace computation and digital simulations back to Alan Turing's early 1950s Morphogenetic drawings, reaction-diffusion algorithms, and pioneering artificial intelligence (AI) in order to establish generative architecture's point of origin. I ask provocatively: *Can buildings think?* as a question echoing Turing's own "Can machines think?" Thereafter, I anticipate not only future bioperformative materials but also theories capable of underpinning strains of metabolic intelligences made possible via AI, synthetic biology, and living technology.

I do not imply that metabolic architectural intelligence will be like human cognition. I suggest, rather, that new research and pedagogies involving the intelligence of bacteria, plants, synthetic biology, and algorithms define approaches that generative architecture should take in order to source new forms of autonomous life that will be deployable as corrective environmental interfaces. I call the research protocol *autopoietic-extended design*, theorizing it as an operating system (OS), a research methodology, and an app schematic for design studios and distance learning that makes use of in-field, e-, and m-learning technologies.

A quest of this complexity requires scaffolding for coordinating theory-driven teaching with practice-oriented learning. Accordingly, I fuse Maturana and Varela's biological autopoiesis and its definitions of minimal biological life with Andy Clark's hypothesis of extended cognition and its cognition-to-environment linkages. I articulate a generative design strategy and student research method explained via architectural history interpreted from Louis Sullivan's 1924 pedagogical drawing system, Le Corbusier's Modernist pronouncements, and Greg Lynn's *Animate Form*. Thus, *autopoietic-extended design* organizes thinking about the generation of ideas for design prior to computational production and fabrication, necessitating a fresh relationship between nature/science/technology and design cognition. To systematize such a program requires the avoidance of simple binaries (mind/body, mind/nature) as well as the stationing of tool making, technology, and architecture within the realm of nature. Hence, I argue, in relation to extended phenotypes, plant-neurobiology, and recent genetic research:

<Architecture = Nature>

Consequently, *autopoietic-extended design* advances design protocols grounded in morphology, anatomy, cognition, biology, and technology in order to appropriate metabolic and intelligent properties for sensory/response duty in buildings.

At m-learning levels smartphones, social media, and design apps source data from nature for students to mediate on-site research by extending 3D pedagogical reach into new university design programs. I intend the creation of a dialectical investigation of animal/human architecture and computational history augmented by theory relevant to current algorithmic design and fablab production. The *autopoietic-extended design* dialectic sets out ways to articulate opposition/differences outside the Cartesian either/or philosophy in order to prototype metabolic architecture, while dialectically maintaining: *Buildings can think*.

For Ronald Christ

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Introduction •

This theory-based proposition and demonstration supports generative architecture in order to advance, theoretically and in practice, the incorporation of metabolic bioremedial systems for design experimentation and prototyping. The proposition is in the form of a pedagogically enabled set of options for considering breakthroughs in science, theory, informatics, robotics, mathematics, and ways to use the resulting data to formulate — construct — learning and research strategies for design. I propose that hybridized theories of autopoiesis (Maturana & Varela 1980) and extended cognition (Clark 2008a) — what I call *autopoietic-extended design* — accommodate methods for research, practice, and learning (Fig 14, p145). These methods guide my reconceptualization and hybridization of technology and architecture as systemically part of nature, and they consequently outline a biological, technological, and theoretical heritage of generative architecture (Canguilhem 1992. Jonas 1966. Odling-Smee *et al.* 2013). Randal Beer foresaw this process of autopoietic hybridization:

Maturana and Varela's notion of autopoiesis has the potential to transform the conceptual foundations of biology [and biogenerative architecture], as well as the cognitive, behavioral, and brain sciences. In order to fully realize this potential, however, the concept of autopoiesis and its many consequences require significant further theoretical and empirical development. A crucial step in this direction is the formulation and analysis of models of autopoietic systems (Beer 2004).

As an evolved formulation of autopoiesis (Maturana & Varela 1980), autopoietic-extended design addresses Beer's concerns via constructivism (Luhmann 1990a) activated through extrapolation and hybridization. In the construction process I sample disciplines of extended cognition (Clark 2008a), artificial intelligence (AI), ALife (artificial life), and living technology by extrapolation and hybridization that gives rise to autopoietic-extended design's procedures (Bedau 2003. Bedau *et al.* 2010. 2013. Garrett 2013. Venter 2012. 2013). In upcoming chapters these procedures interface Alan Turing's (1948. 1950. 1951. 1952. 1953) research in machine thinking (AI), biocomputation, and digital simulation (Dollens 2014). Certain of those procedures are now witnessed in, and illustrated by, a design-generative biodigital research project (Figs 6-10a, pp76-89). The project enacts various morphological experiments responding to autopoietic-extended design precepts in service to pedagogical testing and explanation. And, some of the precepts reside in and inform L-system matrices and armatures — eTrees (Chapters 1. 1.6 & 5. 5.4) — intended to host subsequent biosimulations and morphological as well as metabolic prototyping. Theories of autopoiesis and extended

cognition from herein underpin thesis research, visualization, and computation-establishing procedures linked to software generation and biomimetic observation. Consequently, I categorize the eTrees in what Julian Vincent identifies as a:

... general move towards the production of biomimetic and 'intelligent' materials. ... [in which] biomechanics is neo-morphology. It is morphology plus numbers (1990 ix-x).

Because autopoietic-extended design harnesses specific biological theory to the hypothesis of extended cognition in a framework of intelligence, environment, and technology, it differs from more broadly focused biomimetic investigative strategies. Autopoietic-extended design does not replace biomimetic research; rather, it complements and extends that research with specialized goals and methods. Within autopoietic-extended design I situate human cognition, metabolism, and bacterial sense-making to allow their transference to, or synthesis with, conceptualization and form-finding in aid of intelligent architecture. Cognition and metabolism encompass agency not theorized in biomimetics. So, while I include biomimetic procedures in autopoietic-extended design's tool chest, in my experience biomimetics does not embrace defining, theorizing, recognizing, or incorporating phenomenological, cognitive, and/or metabolic intelligence — neither does it aim to transfer agency to bioremedial buildings. As constituted here, autopoietic-extended design facilitates that transfer.

Therefore, while students/researchers deploy biomimetics to assist them in observing, borrowing, adapting, reformulating, and reinterpreting nature's functions, matter, and methods, autopoietic-extended design helps them devise ways of visualizing and prototyping nature's agency and self-production in order to enact the autonomy of biointelligent buildings. For example, in biomimetically appropriating material properties found in an abalone shell's nacre, the transfer of strength and durability heralds non-toxic biochemical processes suitable for high-performance material laminates whose properties may be duplicated in a laboratory (Benyus 1997). If this same process were being investigated for autopoietic-extended design, research would additionally examine mechanisms of production that includes autonomous self-maintenance, self-monitoring, and self-repair (Cronin 2011. Maturana & Varela 1980. Oxman 2009). Vincent edges close to metabolic performance in his engineering overview:

Biomimicry is leading not only towards materials which have a better mechanical performance but towards materials that can react in some way to the environment [An] intelligent material would act like bone and wood and cause more material to be

deposited in a highly stressed area. This would allow the development of self-designing structures (Vincent 1990 208).

Yet, Vincent (1990) does not advocate research into living, autonomous intelligence. Therefore, while biomimetic/autopoietic share methodologies, autopoietic-extended design mandates a step not necessary for most biomimetic regimens — namely, research into living, self-maintaining, self-monitoring functions and their eventual transfer to bioremedial architecture (Ball 2001. Benyus 1997. Turner 2000. Vincent 1990). For such architecture, this stepped path then requires a mechanism such as extended phenotypes (Chapter 7. 7.4) to conceptually and theoretically induct design, construction, and buildings into a biological milieu (Dawkins 1982. Hansell 2005. Turner 2000). I develop this biological requisite throughout the thesis, but here I signal Scott Turner's words in order to introduce the way that autopoiesis, by requiring agency, moves differently from biomimetics in transforming phenomena, matter, and energy into physical, biological extensions:

Animal-built structures [human constructions included] come into the picture because these are the agents whereby organisms adaptively modify flows of matter and energy [data] through the environment (Turner 2000 212).

Autopoietic-extended design supports conceptual and physical recognition, as well as the organization of living, self-organizing, and phenomenological properties for theorizing and prototyping experimental bioarchitecture. I emphasize again: autopoietic-extended design does not replace biomimetic research; it complements that research with a specialized hypothesis of agency for buildings. Based on the autopoietic/biomimetic distinctions cited above, I contend that design studios deploying biomimetics are oriented differently from studios founded on the living/cognitive focus that autopoietic-extended design addresses. Understanding, for example, that Vincent's biomimetic smart materials are not aligned with metabolic necessity, I advocate a corrective addressed through an autopoietic-extended design operating system (OS). I contend that the OS — biomimetic compatible — will aid in the search for specialized lines of biocomputational and metabolic design research, simulation, and pedagogy for biointelligent architectures. Furthermore, I see autopoietic-extended design as responsive to, dependent on, and partnering with current data-heavy generative programming that I grandfather back to Turing's biological computations and digital simulations (Chapter 5) as well as to Lindenmayer's programming code, L-systems (Chapter 5. 5.4).

I intend autopoietic-extended design to sustain a methodology of operational field research for the transformation of observational and technological data into biologically generative ideas computationally orienting design and fabrication toward metabolically autonomous buildings. Autopoietic-extended design helps organize cognitive production, prediction, introspection, and engagement with computation, machine fabrication, and programmable education. I stress that generative architecture is not exclusively the realm of programming, computation, algorithms, or digital processes. To be generative and ecologically consistent, on-site and laboratory biodigital experimentation must include organization, nurturing, and construction of knowledge, recursively cycling non-linear data found in nature (Frazer 1995. Jonas 1966 202. Luhmann 1990. Lynn 1999).

In this dual generative sense (first-hand observation and digitally processed evolution), input/output recursivity is one of the strengths of computational data plying cognitive and computational force in autopoietic-extended design. Dual recursivity that nurtures both thinking and generative computation privileges research, simulation, and fabrication realized by means of torrential streams of data. Herein, AI, ALife, and machine processing dovetail with cognitive generation involving metabolic, organizational, and environmental events in what Clark calls "agent-world circuits" (2007). Observed in design, agent-world circuits are intentionally constructed prior to what is now commonly accounted for as generative design — e.g., algorithmic computation and computer-numeric-controlled (CNC) fabrication (Gershenfield 2012). Through agent-world circuitry, autopoietic-extended design assists students/designers in situating themselves within a design-by-research practice that interleaves data and biotechnological experimentation on the one hand with the experiential potential of metabolic/intelligent computational simulation and generation on the other.

Achim Menges delineated a related vision in his essay "Polymorphism:"

Based on concepts of developmental biology and biomimetic engineering, the core of such a morphogenetic approach is an understanding of material systems not as derivatives of standardized building systems and elements facilitating the construction of preestablished design schemes, but rather as generative drivers in the design process (Menges 2006 79).

Hereafter I associate "generative drivers" as appropriate to Clark's (2008a. 2013) hypothesis of extended cognition where, to use Almedia e Costa and Rocha's (2005 6) words, "cognition [design thinking here] is no longer modeled as the creation of agent-independent

representations of the world, but as the embodied, evolving interaction of a self-organized system [autopoiesis] with its environment." In this formulation of autopoietic-extended design:

- 1) Nature is viewed as biologically and phenomenologically continuous and autopoietic/allopoietic.
- 2) Animal architectures (including human) are viewed as specialized extended phenotypes.
- 3) The workings of cognition and environment unite via the theory of extended cognition to enable metabolic design visualization.

Throughout the following pages I reflect on Le Corbusier's (2007/1923) aphorism: "a house is a machine for living in" (Chapter 3) relating it through Gosden's (2001) "the house is an intelligent object" (Chapter 6. 6.1), Turing's (1950) "can machines think?" (Chapter 5), and Sullivan's (1979) *form follows function* (Chapter 4. 4.2). I pose these dicta dialectically in order to formulate architecture as a machine/organism hybrid in a *machinic* phylum (Chapters 1. 1.3 & 5. 5.2) (Deleuze & Guattari 1987). Axioms/clichés — Sullivan's *form follows function*, Gosden's *the house is an intelligent object*, Turing's *Can machines think?*, and Le Corbusier's *houses are machines for living in* — invoke powerful ongoing attitudes that ground new experiments for design learning. I do not contest them; rather, I find alternative uses where past clichés support new research.

I contend that the Modernist experiment was never completed and that viable lessons in Sullivan's 1924 book *A System of Architectural Ornament* (1999) may now be reformulated for biogenerative design. Le Corbusier's motto in *Toward an Architecture* (2007/1923) may then be refocused to illuminate challenges of metabolic and intelligent architecture. Adjusted for time and technology, Le Corbusier's house/machine, Sullivan's ornament/rules, Gosden's object/intelligence, and Turing's thinking/machines braid questions of life, cognition, systems, and computation — tractably so, when focused by Maturana and Varela's (1980) biological theory: *Autopoiesis and Cognition* (Chapter 3. 3.1). Sullivan's reframed methodologies rooted in morphology, metabolism, and drawing predate Turing's morphogenetic research (1952), his "imitation game" (the Turing Test 1950), and his universal machine (1936). Yet Turing's biological and computational simulation now make possible *A System's* anachronistic influence on morphological design in rule-generated, icon-derived forms, posited as precursors to algorithmic architecture, simulation, and fabrication (Alexander 1968. 1977. Turing 1952).

Formulating pedagogical and epistemological scaffolding to study metabolic functions for buildings requires an interdisciplinary, hybrid approach. For autopoietic-extended design

that multimodal scaffold factors in technological advancements and architectural history theorized through autopoiesis (Maturana & Varela 1980) and extended cognition (Clark 2013. Menary 2010. Thompson 2007). As a methodological precedent, Félix Guattari (1995) formulated a model in *Chaosmosis* that structures autopoiesis as a theoretical foundation for experimental psychoanalysis; interestingly in the context here, he used this model to address practice involving art, language, and music.

More recently, Patrik Schumacher (2011 v1 & 2) built another type of scaffold that he credits to autopoiesis, but its cross-disciplinary usefulness to metabolic design research is limited in relation to the goals of autopoietic-extended design. This limitation springs from Schumacher's vision of social systems dependent on Niklas Luhmann's (1996) model. Schumacher's (2011 v2 173) deployment of Luhmann's model lacks engaged, clear-cut biological pathways for enacting the animate linkages (unities) required by Maturana and Varela's theory of agency and cognition (Maturana & Varela 1980. 1987). Etymologically, autopoiesis means self-production or self-making and is a theory dedicated to the biological task of defining the minimal properties of independent living systems. Therefore, to call a social system autopoietic necessarily entails discussion of living systems and not a merely prolonged description of social subsystems of communication advocated as autopoietic according to Schumacher's precepts (2011 v1 186).

What must be kept in mind in relation to Schumacher's thesis is that autopoiesis can explain a theory of social systems, but social systems cannot explain a theory of autopoiesis (phenomenological-cognitive living systems). Schumacher maps autopoietic architecture through Luhmann's subset of autopoiesis, not through Maturana and Varela's account of living systems. He writes:

In the conceptual framework adopted by the theory of architectural autopoiesis, the multiplicity of simultaneously operating sign systems is thought to be orchestrated by the unity of a social system — conceptualized as [an] *autopoietic system of communications* — that underlies all human communication processes (Schumacher v2 172 original emphasis).

Schumacher's is then an architectural theory of social systems, not a theory of autopoiesis for architecture. Without an adequate account of autopoietic theory and its ensuing theoretical updates and extensions, Schumacher's *autopoiesis* is both ill defined and noncompliant with Maturana & Varela's (1980) theory. By not distinguishing how and when a system is autopoietic from how and when it is not — that is, how and when his theory of architecture accounts for

buildings as living and cognitive, or how and why it does not — Schumacher perpetuates confusion. Luhmann himself acknowledges the cognitive (living) component where:

... reality of cognition is to be found in the current operations of various autopoietic systems ... [where] the unity of an autopoietic system ... reproduces itself with its boundaries, its structures, and its elements (Luhmann 1990a 72).

Schumacher's autopoietic quest is thus misleading: social systems and subsequent communication systems are consequences of biological (autopoietic) cognitive systems; accordingly, they are not in the position to generate the systems that generated themselves. Following Maturana and Varela (1980 108 i), a social system may temporarily become an autopoietic *composite* when, through a concatenation (coupling) with an autopoietic (living) organization, it becomes a structural unity. At most, Schumacher might specify individual *composite* autopoietic architectural systems (Maturana & Varela 1980 108 i) coupled with living unity, but such specification is not adequate for theorizing his claim to a "general theory of architecture" (2011 v1 4).

To specifically differentiate between Schumacher's autopoiesis and autopoietic-extended design, I stress that autopoietic-extended design investigates theoretical channels through which buildings may be posited and then prototyped as autonomously intelligent — living — in a qualified, non-conscious domain. The conduit I theorize is decidedly different from Schumacher's. I look to autopoietic theory as *evolved* by Di Paolo (2005), Thompson (2007), and Weber & Varela (2002) and as *composed* with Clark's (2008a) theory of extended cognition. I argue that autopoietic-extended design supports the origin of a species of architectural extended phenotypes (Dawkins 1982. Hansell 2005 125. Turner 2000 187. Weber *et al.* 2013) that promote the understanding of human constructions through the conjunction of cognition and matter in the environment (Maturana & Varela 1980 107). This specialized phenotypic extension (Chapter 7. 7.6) integrates phenomenological organization, matter, environmental data, and energy (Nagel 2012) and accounts for bioperformative architecture and communication constituted as autopoietic via: 1) organic or synthetic life, 2) intelligence or sense-making, and/or 3) biorobotic attributes. Autopoietic-extended design accordingly establishes dedicated extended phenotypes as complex adaptive systems (Hansell 2005. Turner 2000) constructed in territory that Maturana and Varela pioneered, contending that living systems: "could be not only reproduced, but designed by man" (1980 83).

Hereafter, my process of interdisciplinary hybridization realizes pathway where autopoiesis intersects with Clark's (2008a) extended cognition for engagements with objects

and environments by following autopoietic criteria to search biological *reasons for designing* with *ways of designing* in order to buttress the emerging OS. *Reasons* and *ways* then ontologically sustain students as they setup in-field, firsthand observational and research practices for environmental occupancy and data sourcing for design (Jonas 1966. Odling-Smee 1996. Odling-Smee *et al.* 2013).

This autopoietic-extended design orientation introduces students to synthetic biology, biorobotics, AI, ALife, and living technologies (Bedau 2003. Bedau *et al.* 2010. 2013. Lewontin 2014), as well as plant intelligence (Brenner *et al.* 2006. Pollan 2013), and biological simulation (Turing 1952. 1953). To many students' surprise, new life forms under investigation for use in industry and medicine are potentially applicable to an emergent, metabolic, generative architecture (Garrett 2013). Leroy Cronin explains:

Buildings would have a cellular structure with living inorganic components that would allow the entire structure to self-repair, to sense environmental changes, establish a central nervous system, and even use the environment to sequester water, develop solar energy systems, and regulate the atmosphere Further, by engineering the cellular system with a standard information network the entire architecture could process and distribute vast amounts of information (Cronin 2011 36).

Given the view of autopoietics as the "self-unfolding of nature" (Riis 2013), a protocol for metabolic architecture — autopoietic-extended design — links synthetic biology and living technology (Bedau 2003. Bedau *et al.* 2013) by means of theory (Clark 2008a. Langton 1988. Maturana & Varela 1980). So linked, metabolism becomes "an ongoing turnover of matter and energy which actively builds the conditions for its own continuation" (Di Paolo 2005a). Via autopoietic-extended design, that continuation enhances metabolic processes building conditions for architectural research (Armstrong 2012. Langton 1988. Spiller & Armstrong 2011. Turing 1952. Weinstock 2006a. b).

As partners, autopoiesis and extended cognition traverse a theoretical network through which students generate ideas prior to computational design generation. Prior observational research and visualization provide data that students may contemplate and program for responsive architectural infrastructures enacting levels of metabolic performance. This pre-computational experimentation ultimately provides the theoretical logistics, organization, or programmatic narrative necessary for positing visualization and data for prototyping (Chapter 5). An example of a multidisciplinary design mindset outside conventional understandings of

biomimetics (because of the inclusion of AI, ALife, and living technology) comes from Rachel Armstrong and Neil Spiller:

Synthetic biology offers new ways to combine the advantage of living systems with the robustness of traditional materials to produce genuinely sustainable and environmentally responsive architecture (Armstrong & Spiller 2010).

Following Armstrong and Spiller, synthetic biology is viewed through descriptions of living technology (Bedau et al 2010. 2013), but I point out that it has it's own further designations:

Synthetic biology is the design and construction of new biological entities such as enzymes, genetic circuits, and cells or the redesign of existing biological systems The elements that distinguishes synthetic biology from traditional molecular and cellular biology is the focus on the design and construction of core components (parts of enzymes, genetic circuits, metabolic pathways, etc.) that can be modeled, understood, and turned to meet specific performance criteria, and the assembly of these smaller parts and devices into larger integrated systems that solve specific problems (Carter *et al.* 2014).

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A core element of autopoietic-extended design's quest for instrumentally aided learning (including medical and scientific visualization and imaging equipment) is in promoting student-design responsiveness to in-field research, synthetic biology, and living technology for compatibility with biogenerative architectural conceptualization (Bedau 2003. Rieffel *et al.* 2013. Spiller 2009). Living technology is hereby outlined from *Artificial Life* as:

. . . based on the powerful core features of life . . . explained and illustrated with examples from artificial life software, reconfigurable and evolvable hardware, autonomously self-reproducing robots, chemical protocells, and hybrid electronic-chemical systems (Bedau *et al.* 2010 89).

With glimpses of living technology emerging, the time is now to experiment with raw and metabolic data from nature — to become comfortable with it as an element of design research. For autopoietic-extended design classes smartphones, apps, and network connectivity redefine infrastructure for pedagogy and university learning domains (Bayne 2010. Fenwick *et al.* 2011). I now view smartphones as liminal species (between technology and on-the-horizon

synthetic life) evolving so rapidly that handsets, apps, and network protocols must be considered in the role that *drosophila* plays for science and genetic testing. Learning domains in turn, evolve simultaneously with student agency and technological practices for cultivating and managing data flows (Gibson 1986). The points of student-to-environment engagement in this process include visualization, coding, drawing, modeling, and machine fabrication — from which, e-literacy draws on students' unparalleled skills acquired from videogames, game strategies, and social media (McGonigal 2011).

In the overall process, I detect smartphone data sourcing and in-field app simulations helping to foreground Turing's (1950) question: "Can machines think?" to reflect: *Can buildings think?* The question, *Can buildings think?* then imbues autopoietic-extended design with an investigatory purpose as well as a troublesome epistemological uncertainty (Barnett 2007. Bayne 2010). From that uncertainty, I unwind arguments to consider landmark biological and technological breakthroughs as impacting architecture from fields such as biomaterials, biorobotics, and biofabrication (Fountain 2013. Garrett 2013. Lewontin 2014). But I caution: my advocacy of smartphones, apps, and mobility, in a program of uncanny design thinking and research does not replace data-heavy computation and programming. In many cases, computational mobility, as typified by smartphone sensors, will facilitate the direct streaming of additional layers of biological and phenomenological data into processes of software generation and thereby into cognitive/computational data streams.

For synthetic biology and technological breakthrough examples, I cite Stanford University and the J. Craig Venter Institute (Markoff 2012) that have announced a fully computational bacterium, while IBM (Markoff 2013. 2014) has announced SyNapse chips (Systems of Neuromorphic Adaptive Plastic Scalable Electronic chips), the first "cognitive chips," not programmed but capable of learning (IBM 2011). The digital bacterium (Covert *et al.* 2012) is a "simulation, which runs on a cluster of 128 computers, [and] models the complete life of the cell at the molecular level." Stanford/Venter's model provides scientists with "computerized laboratories" from which they may experiment "without the need for traditional instruments" (Markoff 2012). Related and updating the above, in May 2014, *Nature* online reported a synthetic code inserted in a "cell that propagates with unnatural nucleic acids in its DNA" (Malyshev *et al.* 2014. See also Pollack 2013. Venter 2013). For balance, Lisa Garrett (2013) discusses dangers as the revolution in synthetic biology more fully engages.

Where biological and technological hybridization involves metabolic intelligence and environmental performance, living technology and robotic design are far in advance of architecture in deploying biosensory intelligence and synthetic life (Bedau *et al.* 2010. 2013. Pollack 2013. 2014). To catch up, architecture will require experience with laboratory

equipment in support of design initiatives as well as experimentation consistent with the observation that "traditional architectural and engineering ways of thinking about materials as something independent of form and structure are obsolete" (Weinstock 2006b 35-36). Generative architecture now stands in need of scientific imaging and advanced scanning equipment of its own — new types of visualization equipment, design labs, tools, and research facilities (Jorgensen 2012) that can logically evolve existing fablabs (Gershenfeld 2012) in order to enable bio-experimentation coordinated with the aims of metabolic design ecology (Armstrong 2010. Frazer 1995. Spiller 2009).

If synthetic bacterium and SyNapse chips foretell as yet unknown lines of scientific experiment, they nevertheless exist as mainline research. Other examples of emergent yet equally rigorous new investigations should be sought. Carter *et al.* (2014) suggest:

An integral feature of synthetic biology that will enable rapid advancement in genetic engineering is the application of an engineering [or architectural] mindset to biology. Essentially to this mindset is the ability of scientists and engineers to think of DNA not as strings for nucleotide base pares (A's, T's, G's, and C's), but instead as parts, devices, and systems. These components can then be used and combined in new ways to achieve different outcomes This approach also opens the door for people other than traditionally trained biologists to use genetic engineering for broader range of applications (Carter *et al.* 2014).

Living technology and biorobotics (Bedau *et al.* 2010) exemplify the potential of non-conscious intelligence (AI, A-life, simulated bacteria) possessed by even the most basic single-cell life — which no machine or building *yet* possesses (Varela 1997 79). More controversial, but critical to metabolic architectural experiments, are alternative models of animal and even plant cognition and intelligence (and subsequent problems of consciousness). Where plants are concerned, we may be seeing a paradigm shift involving previously unknown types of biochemical memory implicating intelligence through the new discipline of "plant neurobiology" (Brenner *et al.* 2006. Gagliano *et al.* 2014. Pollan 2013).

Visualizing intelligent materials from nature and through biological means could, for example, influence the design of pliable building skins able to fold like a leaf (Focatiis & Guest 2002) thereby offering shape-shifting morphological possibilities to facades then capable of performing aerodynamic efficiency (Rieffel *et al.* 2013). Rachel Armstrong has considered how synthetic biology can contribute to such visualization:

The building envelope could be constructed not with . . . traditional inert surfaces . . . [but] with a 'living' cladding, which could house a range of synthetic-biology-based technologies (Armstrong 2012 loc 483).

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With the performance of a leaf (Figs 2, p44. 3, p45) as a model of nature-to-architecture interfacing, buildings may become environmentally relevant and proactive (Hitt 2014. Montebelli *et al.* 2013. Wallis 2013).

A building's ontological reasons for being are our reasons, our survival extensions resembling those of extended phenotypes (Clark 2001b. Dawkins 1982. Hansell 2005. Turner 2000. Weber *et al.* 2013). Extending examples of design and architecture rationally, buildings could also be sustainably fitter if they were equipped with performative biological capabilities evolved from non-conscious intelligent systems (Brenner *et al.* 2006. Mancuso 2010). Changing a building's membrane/structure will metabolically impact architectural ontology through functions participating in urban sensing, bioprocessing (photosynthesis etc.), and signaling. Recalculating the ontological state of a building from inert to intelligent (via bio- and synthetic-life materialization) will change its status in nature, increasing the building's fulfillment of its architects' social responsibilities as well as their recognition of its bioremedial value (Oxman 2011). Performative intelligent facades thus become indicative of first-generation metabolic architecture (Webb 1996. 2001. Wallis 2013). Fully metabolic systems are a next step (Cronin 2011. Spiller 2009. Spiller & Armstrong 2011. Venter 2013).

Lifelike computing systems and AI are emerging after decades of experiments theoretically supported, though not conceptualized, in Alan Turing's papers "Intelligent Machinery" (1948), "Computing Machinery and Intelligence" (1950), "The Chemical Basis of Morphogenesis" (1952), and "Morphogen Theory of Phyllotaxis" (1953). Turing's papers underpinned possible computation with far-reaching implications for today's technologies (Brenner 2012. Reinitz 2012). From these and other writings, drawings, and simulations by Turing, I site the origins of generative architecture; but most specifically, I locate Turing's influence from his morphogenetic research undertaken after joining the University of Manchester (Copeland 2012. Dollens 2014. Richards 2013. Swinton 2004. 2013).

Concepts stemming from this period of Turing's research (1948-1954) are still being evolved, still branching through iterations of his imitation-game (Turing Test) and reaction-diffusion morphogenesis (Prigogine & Nicolis 1976. Reinitz 2012. Turing 1952). These concepts now underwrite the reexamination of "Can machines think?" (Dennett 1998. Turing 1950). John Reinitz wrote in *Nature* that Turing's algorithmic models in this period evidenced "the first computer simulations of [biological] pattern formation . . . What Turing should receive credit for

is opening the door to a new view of developmental biology” (Reinitz 2012 464).

So, if asking *Can buildings think?* sounds paradoxical, I maintain that it, like Turing's question, is phenomenologically, biologically, and computationally complex (Turing 1950) — meaningful in an era of pervasive mobile computing (Pew Research 2013), living technology, and synthetic intelligence (Bedau *et al.* 2013. Garrett 2013. Lewontin 2014). Turing's question now generates desirable dialectic friction I capture in the attempt to escape the shelter that design took in past binary clichés of real/artificial, mind/body, and analytic/synthetic. Those binaries uselessly segregated thinking from doing and buildings from nature (Clark 2008a. Luhmann 1990a). Neri Oxman, in "Protocell Architecture" signals this movement when she writes:

To conceive of design as the "dry path" of biology in the generation of synthetic form requires designers to find the formula to describe matter as generative. To do this, they must first abandon the conceptual structure of a divided and hierarchical process separating the analytic and the synthetic, and arrive at their ultimate integration. A new philosophy of design is slowly emerging which anticipates and supports the merging of matter and energy on the way to proto-design (Oxman 2011 105).

Autopoietic-extended design provides one theoretical integration that Oxman anticipates. In addition, design researchers today overcome Cartesian divisions when they model metabolic functions for architecture as part of systems "integration . . . merging matter and energy on the way to proto-design" (Oxman 2011 105. Nagel 2012). In this light, Turing's (1950) "Computing Machinery and Intelligence" and his morphogenetic research (Turing 1952. 1953) are symbiotic (Margulis 1999) — conjoined — they create an autopoietic domain for considering cognition, machine intelligence, and biology (Wells 2004). Seen within a symbiotic continuum of nature, technology, and mathematics, Turing's work facilitated the integration of 1960s and 1970s botanic coding (L-systems), computational biology, and generative architecture (Chomsky 1959. Floreano & Mattiussi 2008. Hayles 1999. Lindenmayer 1968. Prusinkiewicz & Lindenmayer 1990. Richards 2013).

Without explicitly referencing Turing, and in a retrospective view, Varela *et al.* (1974) helped carry forward the computable visions of machine intelligence and morphogenesis with his, Maturana's, and Uribe's (Chapter 1. 1.3) autopoietic cellular automaton (Langton 1988. McMullin & Varela 1997. Ray 1994. Turing 1952. Uribe 1981. Varela 1979). Turing's observations of plants had already exemplified origins at which data was decoded from nature (1952. 1953) for hand-plotted drawings as well as for algorithmic computer simulations,

thereby establishing precedents for digital botany (Bentley 2001. Reinitz 2012) and later parametric generative software (Chomsky 1959. Dollens 2014. Lindenmayer 1968. McMulling & Varela 1997. Richards 2013. Swinton 2004. Uribe 1981. Varela *et al.* 1974).

Placed against the backdrop of Turing's algorithmic morphology and pioneering digital simulations (Chapter 5), Maturana and Varela's (1980) theory of autopoiesis articulates biological properties necessary for theoretically conceptualizing and categorizing living systems and AI that autopoietic-extended design relies on to recognize metabolic/intelligent agents for architecture. Against that backdrop, and on the basis of their own text, Maturana and Varela charted a theory of life and cognition that has been continuously amended by later cognitive scientists, biologists, engineers, and philosophers (Beer 2004. Di Paolo 2005. Thompson 2007. Weber & Varela 2002). Original autopoiesis theorized the minimal components for defining life/cognition in nature (Maturana & Varela 1980). The amended theory (De Paolo 2005. Maturana & Varela 1980. Weber & Varela 2002), rooting here and applied via extended cognition (Clark 2008a) accommodates AI, computational biology, living technology, and biosimulation (Armstrong 2012. Clarke & Hansen 2009. Luhmann 1990. Hayles 1999. Spiller 2009). Specifically, it gives autopoietic-extended design the ability to aid students in distinguishing and recognizing metabolic performative properties potentially appropriate to design experimentation.

Autopoiesis from its origin, and through subsequent amendments, still considers computation and machines in processes of life (Zeleny 1981). Hereafter, either by contextual implication or metaphorical subscription, I follow Heinz von Foerster:

[T]he term "computation" will be . . . applied to all operations (not necessarily numerical) that transform, modify, re-arrange, order, etc., either symbols (in the "abstract" sense) or their physical manifestations (in the "concrete" sense). This is done to enforce a feeling for the realizability of these operations in the structural and functional organization of either grown nervous tissue or else constructed machines (von Foerster 1972).

Tracking von Foerster's sense of computation, and recognizing its synthesizing intention, I place its ideas in service of Turing's hand drawings simulating organic growth and biochemical reactions (Richards 2013. Turing 1952). I then discuss the drawings and simulations (Chapter 5) to further support the hybridization of:

- 1) Biological self-organization via autopoiesis (Maturana & Varela 1980) and,

2) cognition-to-environment communication and simulation via extended cognition (Clark 2008a. 2013a).

Both autopoiesis and extended cognition function through cognition and computation (illustrated by Turing's twofold practice of drawing/simulation) as I bring them together to instantiate autopoietic-extended design. First I consider autopoiesis as:

... a singularity among self-organizing concepts ... provid[ing] the decisive entry point into the origin of individuality and identity ... connecting ... into the [living] phenomenological realm (Weber & Varela 2002 116).

I then hybridize autopoiesis with extended cognition, encapsulated by:

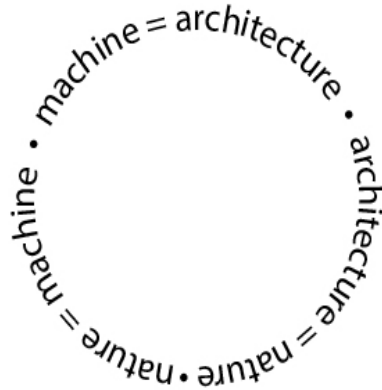
It is possible that sometimes at least, some of the activity that enables us to be the thinking, knowing, agents that we are occurs outside the brain? ... Minds like ours are the products not of neural processing alone but of the complex and iterated interplay between brains, bodies, and the many designer environments in which we increasingly live and work (Clark 2010b).

Together, and over the course of hybridization, definitions of autopoiesis are elaborated on in order to formulate autopoietic-extended design as a skeletal OS for investigating biological input/output in the development of metabolic/intelligent generative architecture and theory. Once acquired, raw data from nature requires that "origin of individuality and identity" (Weber & Varela 2002) be articulated in order for the thinking of the architect or student to construct autonomous, metabolic, and intelligent works from it.

Afterwards, coded and scripted architecture requires that the architect translate/design processes for furthering the integration of data as information (into materials and systems) defining how living technology is to function in the context of a building (Luhmann 1990. Varela 1981). From this autopoietic-extended design process, students evolve building research to mediate environments (Clark 2008a) *tuned by* their thinking as well as *attuned to* (Coyne 2010) bioremedial tasks via living technology in order to question: "Can buildings think?" (Armstrong 2012. Spiller & Armstrong 2011. Bedau 2003). As Coyne (2010 xv) defines it, tuning "is an interpretive and relational process concerned with contingent human interactions and participation in human solidarity." That "process" is here interpreted as a method and practice for implementing autopoietic-extended design through "micropractices by which designers and

users engage with the materiality of pervasive digital media and devices” (Coyne 2010 xv).

Compiling autopoietic-extended design processes for student use, I strategize the transfer of theory into practice. Nurtured flows of information (Gibson 1986) then provide "continuous reciprocal causality" (Hayles 2012 102) acknowledged here in genetic, evolutionary, and phenomenological processes expressed in physical buildings as extended phenotypes (Dawkins 1982. Hansell 2005. Langton 1988. Weber *et al.* 2013). This theoretical construct may be expressed in an iterative equation:



nature = machine:

machine = architecture:

architecture = nature.

Consider: we build machines when we build architecture — architecture is a big machine anchored in the ground. Thus, since architecture is a big machine and the problems of machines may be seen as heuristic (think, for example, of what smartphone/apps as models of intelligent machines could teach architecture), the problems of technology, intelligence, and metabolism that exist for machines (Turing 1950. 1952) comparably exist for architecture and cities (Greenberg & Jeronimidis 2013. Komninos 2013). In this formulation these questions are parallel:

“Can machines think?” = Can buildings think?

I'm not — *yet* — claiming the precepts are true; only that they are, vis-à-vis Turing's (1936. 1950) thinking machines and theory, legitimately self-similar.

A Clark (2008a), Turing (1952), Dawkins (1982), Di Paolo (2005), and Maturana and Varela (1980) theory-hybrid can support learning and designing with autopoietic-extended design as its evolving OS. That OS, to use Hayles's words: “intervene[s] in the cycles of continuous reciprocal causality [feedback]” (Hayles 2012 102). With feedback understood as cognition-to-

environment "reciprocal causality," we may then physically, technologically, and/or phenomenologically nurture data recursion as a learning component because it is theoretically embodied in autopoietic-extended design by virtue of autopoietic self-organization (Weber & Varela 2002). Furthermore, the deployment of theory guides environmental occupation (use, habitation, learning) as it impacts analogue and digital evolutionary processes funneling bio-data into research and then into materials and architecture (Hayles 2012. Jonas 1966. Odling-Smee *et al.* 2013).

The autopoietic-extended design program may now be seen as participating in Maturana and Varela's (1980 82-83) Turing-compatible formulation (living systems will eventually be human made) that I use to frame *machinic* intelligence and metabolism (Chapter 2), smart materials, and biological systems as contributors to generative building research (Clark 2008a. Deleuze & Guattari 1987. Maturana & Varela 1980. Turing 1950). To recap that sequence, cultivated design ideas feedback from the observation of nature (sometimes via technology), registering data manifested as information for research (Luhmann 1990. Turing 1952). In this process of feedback, we may tune information's flow and affordances (Coyne 2010. Gibson 1986) as sources of insight from nature and biology, or as *components* and *unities* in autopoietic *domains* (Clark 2008a). Collecting data-from-nature for construction of research information then becomes fundamental to design development, generative design methodology, and architectural pedagogy.

Having repeatedly referred to both data and information in the course of this text, I now want to differentiate them, as per Varela:

[I]nformation does not exist independent of a context of organization that generates a cognitive domain, from which *an observer community* can describe certain elements as informational and symbolic. Information, *sensu strictu*, does not exist. Nor do, by the way, the laws of nature (Varela 1981 45 original emphasis).

I distinguish data as the raw material of information feeding cognitive (and technological) domains from nature, objects, and buildings. Hereafter, information and knowledge denote phenomenological constructs of human cognition from which observer communities (students) construct reality (Fenwick *et al.* 2011. 6. See also Lettvin *et al.* 1959). Niklas Luhmann maintains information as wholly phenomenological:

... what is usually called "information" are purely internal achievements. There is no information that moves from without to within the system. ... [information] doesn't

exist in the external world, but is a construct [an extended phenotype] (Luhmann 1990 69).

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In metabolic generative architecture, buildings will act autonomously *from* intelligent feedback and then act *with* feedforth to prompt reactive infrastructural actions that address interior and exterior conditions such as noise, toxins, allergens, temperature, light, wind, moisture, and energy consumption (Armstrong 2011. 2012. Bedau *et al.* 2010. 2013). Living technologies (Garrett 2013. Lewontin 2014) offer architecture degrees of intelligence or sense-making (Di Paolo 2005) exemplified in biorobotics (Harmon Courage 2014. Webb & Consi 2001) and hinted at for urban-scale architecture by Hamburg's Bio Intelligent Quotient (B.I.Q.) building (Wallis 2013).

To achieve compatibility with metabolic functions, generative architecture requires programming and learning to interface new conceptions of materials, life, technology, visualization, and performance. The autopoietic-extended design scaffolding that emerges here programs and organizes performance exercises toward this end (Appendix 1). Student Handbook exercises are tied to class goals and new ways of learning geared to active on-site optical and technological (smartphone/app/data) research occupation. In this program, autopoietic-extended design allows for a shift from theory to application enabling in-field classes by structuring pedagogy and environments as autopoietic unities: *student + technology + program + environment* activate its pedagogical scaffold (Figs 1, p29. 2, p44. 3, p45. 11, p93. 29, p278. 30, p279 & Appendix 1). In this regard, Richard Dawkins's Biomorph experience with digital simulation becomes insightful:

I have really been led to think differently as a result of creating, and using, computer models of artificial life which, on the face of it, owe more to the imagination than to real biology. The use of artificial life, not as a formal model of real life but as a generator of insight (Dawkins 1988 201).

In parallel, I suggest that the OS supports and facilitates "think[ing] differently" as "a generator of insight" organized to address:

- 1) Procedures by which theories drive autopoiesis and extended cognition to help students initiate research protocols and methods in architectural studio-based and m-learning practices constructed by sourcing data from nature, algorithmic simulations, and living technology.

- 2) The usage of conceptual scaffolding to support cross-disciplinary design research and visualization involving metabolic and synthetic life that will, in turn, fortify generative architecture computationally rooted in direct physical and technological observation, simulation, and machine fabrication.
- 3) Cultivation of multidisciplinary collaborations that theoretically or historically invent, source, recognize, or prototype biointelligent systems involving material hybrids and living or synthetic life.

Sketched in these terms, I present autopoietic-extended design as enhancing generative architecture's evolutionary adaptability (Di Paolo 2005. Floreano & Mattiussi 2008. Frazer 1995) by increasing the possibilities of selection from metabolic organisms in order to transfer ecological responses found in nature to bioperformative architecture (Clark 2012. Di Paolo 2005. Weber & Varela 2002). Evolution (Maturana & Varela 1980 104-105) is itself elemental within autopoiesis (1980 96); it drives implementation of selection engaging extended cognition when hybridized with autopoiesis (Di Paolo 2005. 2010). Out of such confluences, new approaches to design theory and research self-organize (Weber & Varela 2002 116) and may be prompted to aid autopoietic-extended design's role in the construction of architectural knowledge (Maturana & Varela 1980 5):

No matter how much we think we understand biological problems today, it is apparent that without an adequate theory of autopoiesis it will not be possible to answer questions such as: "Given a dynamic system what relations should I observe between its concrete components to determine whether or not they participate in processes that make a living system?" (Maturana & Varela 1980 114).

Until such a question as "What relations should I observe?" is posed and responded to vis-à-vis living systems, generative architecture cannot evolve toward biogenerative, metabolic intelligence. When biology, ALife, and living technologies are not factored into near-future architectural education, a schism results — design learning drifts outside parallel innovative domains that feed aviation, electronics, synthetic biology, and medicine. Autopoietic-extended design bridges this schism and attempts an OS-procedural response that gives research and theory a new, specialized orientation focused on living/cognitive architectural systems. Addressing Maturana and Varela's above question, upcoming case studies focused on Louis Sullivan (Chapter 4), Alan Turing (Chapter 5), and archaeology (Chapter 6) frame biogenerative architecture and autopoietic-extended design as:

- 1) United cognitively and environmentally against binary divisions thereby minimizing a priori visualization.
- 2) Made coherent by theory and philosophy in an autopoietic framework.
- 3) Understood to generate design insight (ideas, discussions, experiments, research) before or simultaneously with computationally generating forms.
- 4) Understood to technologically seek and translate metabolic and morphological data from nature into design, biosimulation, and bio-intelligent building performance.
- 5) Understood as operational through metabolic and/or synthetic intelligence hybridized between cognition, environment, and technology.
- 6) Understood to posit architecture as equivalent to extended phenotypes thereby situating building, fabrication, and communication as continuous with nature.
- 7) Understood to deploy biological and synthetic intelligence not (necessarily) modeled on human cognition, but measured in terms of sense-making on the order of single-cell organisms and/or plants to ontologically reconceptualize architecture vis-à-vis nature.

These concepts and procedures underwrite autopoietic, cognitive, environmental, computational, and pedagogical domains for interacting within the autopoietic-extended design OS. The points support autopoietic-extended design learning and research for evolving metabolic agents and/or biotechnologies, that when paired and hybridized, for example, with AI and synthetic biology (Bedau *et al.* 2013), inform new generative design practice (Fenwick *et al.* 2011. Hensel *et al.* 2010. Weinstock 2006a b). By sourcing cognition, theory, biology, data, and technology, the above seven-point schema outlines an autopoietic and extended cognition matrix hybridized for a bio-constructivist learning program (Luhmann 1990a). As we shall see in the following chapters, transferring the dialectical theory to a programmatic OS scaffold, autopoietic-extended design helps students reconceptualize, retool, and recategorize architecture as evolving toward a metabolic, bioperformative, and bioremedial collaboration with nature (Armstrong 2012. Jonas 1966. Odling-Smee *et al.* 2013. Spiller & Armstrong 2010).

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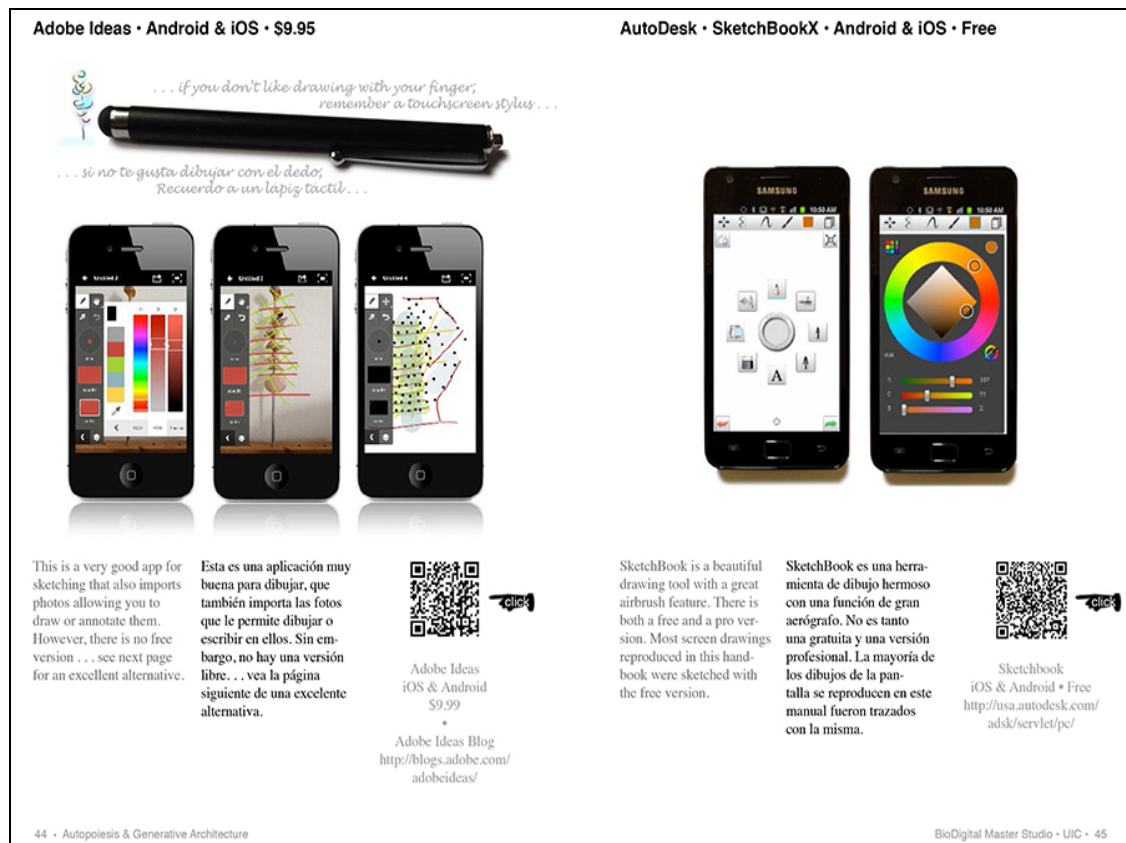


Fig 1. Student Handbook (Appendix 1). Two Handbook pages discussing and illustrating production apps suitable for student in-field design and documentation. Drawings/text: Dennis Dollens.

Chapter 1 • Can Buildings Think?

In an age experimenting with biological chips, algorithmic intelligence, and biosynthetic life, architectural research and learning could access new frontiers of procedural and pedagogical roles to envision buildings as metabolic and intelligent (Armstrong 2010. Bedau *et al.* 2010. Boden 2000. Church & Regis 2012. Garrett 2013. Venter 2013). Already in this era, students deploy ever-increasing computational power and communication abilities using smartphones and apps (Oxford Internet 2013). They mediate their physical and social worlds by means of unprecedented technological access to data, mapping, tracking, augmented environments, games, media — and, for some, design apps. "Nature," for many members of this group:

[B]ecomes knowable through the intermediary of the sciences; it has been formed through networks of instruments; it is defined through the interventions of professionals, disciplines, and protocols; it is distributed via data bases; it is provided with arguments through the intermediary of learned societies (Latour 2004 loc 72).

Considered in Bruno Latour's sense, architectural education and research may be sited as similarly distributed in culture and technology: "knowable through the intermediary of the sciences . . . [and] learned societies" (Latour 2004 loc 72). In Latour's theoretical realm, technology as discussed here, is a connective tissue bonding metabolic intelligence and nature — part of an extended cognitive network Andy Clark portrays as:

. . . the emerging unifying vision of the brain as an organ of prediction using a hierarchical generative model. Recall that, on these models, the task of the perceiving brains is to account for (to "explain away") the incoming or "driving" sensory signal by means of a matching top-down prediction. The better the match, the less prediction error then propagates up the hierarchy (Clark 2013 185).

Factored into an educational equation of risk-to-reward or the "uncanny," university-level e-learning as formulated by Siân Bayne, becomes both an ontological mode in Clark's sense and a mode of knowledge construction in Bruno's sense:

. . . the digital represents not an enhancement to, extension of, or substitute for familiar, offline practices. Rather, it is a privileged mode, one in which new ontological positionings, and new dispositions toward teaching and toward knowledge might be explored and delighted in (Bayne 2010).

Knowledge construction, cognition, and technology conscripted for design from Bayne's, Bruno's, and Clark's quotations, provision core ideas I use to build scaffolding for architectural learning, research, and production. That preliminary infrastructure is then heavily braced by autopoiesis (Maturana & Varela 1980) and extended cognition (Clark 2008a. Di Paolo 2008. Thompson 2007). In effect, I seek missing components in currently conceived generative architecture (concentrated on code, machines, and fabrication) to join with theory and cognitive-technological idea generation searching for ways to input metabolic functions into building design.

To do so, I look for architectural thinking and design input/output prior to algorithmic and machine production output. I search methods to generate ideas based on data (Luhmann 2000) from nature in order to transfer it via technology and observation to design. Herein, autopoiesis and extended cognition base investigation of metabolic sensing, morphological communication, and biomimetic design research. The scaffolding is intended to give students and researchers access to data to further support analytical methods compatible with educational theory from Bayne's (2010) sense of "ontological positionings." I read Bayne's position inline with Hans Jonas's environmental philosophy:

Analysis has been the distinctive feature of physical inquiry since the seventeenth century: analysis of *working* nature into its simplest dynamic factors. These factors are framed in such identical quantitative terms as can be entered, combined, and transformed in equations. The analytical method thus implies a primary *ontological reduction* of nature, and this precedes mathematics or other symbolism in its application to nature. Once left to deal with the residual products of this reduction, or rather, with their measured values, mathematics proceeds to reconstruct from them the complexity of phenomena in a way which can lead beyond the data of the initial experience to facts unobserved, or still to come, or to be brought about. That nature lends itself to this kind of reduction was the fundamental discovery, actually the fundamental anticipation, at the outset of mechanical physics (Jonas 1966 200 original emphasis).

Jonas's blended environmental and philosophical scrutiny predates more recent thinking about autopoiesis by Francisco Varela (Weber & Varela 2002), Evan Thompson (2007), and Ezequiel Di Paolo (2005. 2008. 2010) developing an essentially biomimetic (Benyus 1997. Weinstock 2006a) perspective compatible with Bayne's (2010) pedagogical positionings and Clark's (2008a) environmental synthesis. Both Bayne and Jonas leave processes to be defined

and ontologically occupied as part of learning. For Bayne the *uncanny* (2008. 2010) is situated in the unfamiliar, risky territory of exploratory digital media deployed for learning. And, Jonas prompts us to consider Turinglike (Chapter 5) observation to reveal "*ontological reduction of nature*" as "preced[ing] mathematics" (Jonas 1966 200).

Paired, Bayne and Jonas generate a creative friction from which I question how architecture will deal with *living technology* (Bedau *et al.* 2010) and issues of intelligence that, by default, position nature and technology as inseparable components of generative design. Uncanny and risky friction (Bayne 2008) further registers the "complexity of phenomena in a way which can lead beyond the data of the initial experience to facts unobserved, or still to come, or to be brought about" (Jonas 1966 200); that sounds like education and knowledge construction useful to unpack in uncanny digital scholarship.

If, in animate domains, we look to distinguish metabolic and intelligent functions (Luhmann 1990a 76) for design and buildings, or in cultural domains we look for categories of machine intelligence and non-cognitive states associated with plants and lower animals (Brenner *et al.* 2006), then describing minimal life (Maturana & Varela 1980) becomes an investigatory process relevant to design performance and learning. With the use of observation and distinction, constructivist paths may be blazed where "observation occurs when thoughts that have been processed through consciousness fix and distinguish something" (Luhmann 1990a 78).

Observation mixed with technically accessed data is then available to students to hybridize (agent/machine), becoming operative for reinterpreting nature and metabolism in design projects via theory as generative of rules or procedures (Chapter 4). The "crossing of genetically distinguishable groups or taxa, leading to the production of viable hybrids" (Mallet 2005) defines hybridization in the sense of recombination expressed in newly blended data sets that in architecture lead to extended phenotypes (Dawkins 1999) and niche constructions (Odling-Smee 1996):

In the mid-nineteenth century, Darwin explored the nature of species by interbreeding them and demonstrating that mating between groups can be difficult (Darwin, 1859). Surprisingly, however, hybridization between species in nature is not as uncommon as this early result would imply (Mallet, 2005). After Darwin, botanists and zoologists took different paths to understanding hybridization Since then, scientists have been able to uncover many examples of hybridization across several branches of life. This evidence initially came from fossil or extant species morphology, but more recently, molecular tools have enhanced hybridization research in a wealth of biological systems

(Mallet, 2005). Over the last 50 years, the study of hybridization has yielded valuable insights, not only refining scientists' systematic understanding of the taxa involved, but also helping researchers understand those forces that limit hybridization, as well as how gene flow and recombination can act to generate haplotypes [combination of DNA sequences] to facilitate adaptation (Stevison 2008. See also Mallet 1995. 2005)

Reinterpreting nature via hybridization and technology has sometimes been referenced as (human/machine) cybernetic processes directed to overcoming perceived obstacles in nature (Hayles 1999). But today, considering smartphone sensors and approaching living technology, it is more akin to human/machine symbiosis. In this realm, synthetic life, AI, and biology are likely to interface animate and inanimate constructions as sense-making controllers or, in cybernetic speak, the *helmsman*, in collaborative negotiations with nature (Clark 2003. Clarke & Hansen 2009. Haraway 1990. Hayles 1999. Margulis 1999. Wolfe 1998).

Observing nature (optically and technologically) for design input reveals the need to cultivate data flow (Gibson 1986) as a type of literacy in order to better serve primary investigation and, to make apparent and then integrate, breakthroughs in science and technology as relevant to architectural production and design learning. I classify smartphones as the embodiment of cyborgian dreams of ubiquitous or even prosthetic computing and therefore as intellectual and existential aids (Clark 2003. Haraway 1990. Hayles 1999. Latour 2004. Wolfe 1998. 2010).

Smartphones represent technological connectedness as well as technological extension into the environment (Clark 2008a). Along with apps, they further serve to bond machines and intelligence to each other vis-à-vis code programming. I use this pairing to relate design research through smartphones as AI machines bridging metabolic and inorganic nature. Jonas (1966) defines metabolism in black and white: "every living has it, no nonliving has it" (Quoted: Weber & Varela 2002). Hence, he provides a rule-of-thumb, distinguishing life-systems compatible with autopoiesis and extended cognition (Clark 2008a. Maturana & Varela 1980).

For students, such a designation defines the parameters of learning and the spatial occupancy that balance, in Bayne's sense of "ontological positionings," the ways in which technology and nature may be interfaced (Bayne 2010). With "ontological positionings" and Jonas's (1966 200) evocations of the "ontological reduction of nature" in mind, metabolism itself may be approached through Di Paolo's definition, in the context of autopoiesis and extended-mind theory:

... *metabolism*, a self-affirming process of constant regeneration of form amidst a flux of

matter and energy. This level of physical organization seems to have the necessary existential credentials: 1. the establishment of a distinct "self" for which being is its own doing and with physical and organizational distinction between inside and outside, 2. an entity which is in constant environmental challenge, in need of material turnover and with the freedom to achieve it, and 3. the establishment of a normativity following the logic of metabolism according to which otherwise neutral events, both internal and external, can be good or bad for the continuation of the organization (Di Paolo 2005 original emphasis).

Di Paolo (2010), furthers Jonas (1966) on metabolism relevant to life as contrasted to matter:

An organism, in contrast, is *defined* by the fact that it never actually coincides with its material constitution at a give instant and yet maintains a form dynamically. Due to its metabolism, its components are in constant flux. However, they sustain an organization that promotes its own durability in the face of randomizing events that tend towards its dissolution. The organism has a formal and dynamic identity. It only coincides fully with its material constitution when it is dead (Di Paolo 2010 137 original emphasis).

Through concepts of metabolism and minimal definitions of life held by Maturana and Varela (1980), Jonas (1966), and Di Paolo (2005, 2010), I maintain *Autopoiesis and Cognition* is biologically pertinent to generative architecture looking to nature. Pertinent as scaffolding, in much the same way Guattari's *Chaosmosis* appropriated autopoiesis to support psychoanalysis focused on subjectivity (Guattari 1995/1992). By searching nature a student is confronted with data available to design visualization and systems integration within building performance. Autopoiesis asks of metabolism and cognition: "What is the organization of the living?" and "What takes place in the phenomenon of perception?" (Maturana & Varela 1980 xii). These questions, in parallel with research into metabolic processes desirable for architectural performance, encompass systems of cognition, perception, intelligence, and learning outside traditional body/brain contexts or the architect as heroic visionary.

Clark (2008a), Gibson (1986), Jonas (1966), Luhmann (1990a), and Thompson (2007 222) provide the cognitive-environmental interface that autopoiesis and extended mind theories present against dualisms. From that interface, cognition is registered as metabolic processes contingent and collaborative with environments, objects, and nature (Clark 2008a, Clark & Chalmers 1998, Di Paolo 2010, Menary 2010, Noë 2009, Thompson 2007). Therein, from

a nondualistic perspective, I find Di Paolo's definition of cognition compatible with generative architectural goals:

... an embodied engagement in which the world is brought forth by the coherent activity of a cognizer in its environment. ... this engagement involves the structuring of the immediate milieu with the consequent building of regularities, which feed back to the organism itself (Di Paolo 2008 12).

I apply Di Paolo's idea of "embodied engagement" to architecture noting however, that through autopoietic-extended design, the "cognizer" will be a structure, object, or building not based on human thinking, yet potentially modeled on or with collectives of single-cell organisms. For perspective, Maturana and Varela (1987) outline cellular autopoiesis in amoeba and bacteria in *The Tree of Knowledge*, and Adamatzky's (2013) ongoing experiments with problem-solving amoeba are discussed later.

To formulate autopoietic-extended design, I begin with Wikipedia's entry for *autopoiesis* as a group-sourced definition; thereafter progressively selected, adapted, and evolved in these pages. First, though, I point out that when academically possible, I call upon Wikipedia because of its ground-up aggregation of information and the important role the website plays in student research and digital and mobile scholarship. Nevertheless, in many cases where I cite Wikipedia, I later reference additional sources. The Internet resource begins its entry with:

Autopoiesis (from Greek *αὐτο-* (*auto-*), meaning "self", and *ποίησις* (*poiesis*), meaning "creation, production") literally means "self-creation" and expresses a fundamental dialectic among structure, mechanism, and function. The term was introduced in 1972 by Chilean biologists Humberto Maturana and Francisco Varela (Wikipedia 2013a).

From that bare-bones formulation, I look to Randall D. Beer because he, like Di Paolo (2005), not only recognized that autopoiesis must evolve, but also aligned his adaptations with algorithmic programming, making them relevant to generative architecture. Beer's paper, "Autopoiesis and Cognition in the Game of Life" begins:

Autopoiesis is a network of component-producing processes with the property that the interactions between the components generate the very same network of processes that produce them [SIC], as well as constituting it as a distinct entity in the space in which it exists. The paradigmatic example of autopoiesis is a cell, in which the components are

molecules, the interactions are chemical reactions and the cell membrane serves as a physical boundary that spatially localizes these reactions into an entity (or "unity") distinguishable from its environment. . . . Maturana and Varela offer a view of life as a specific organization of physical processes that has as its principal product the maintenance of its own organization (Beer 2004 310).

My analysis postulates an autopoietic interface for use in architectural learning and research — predominantly digital and biogenerative — mediated by science, computation, and technology, and sourced in nature. I conclude that such an interface, instantiated by students and designers as thinking agents, is inseparable from the "reality of the external world, [and] hence part of nature," to use Weber and Varela's (2002 104) formulation of humans vis-à-vis nature. Georges Canguilhem came to a similar conclusion and relied on Descartes for theoretical support:

[W]e arrive at the point where the machine is seen as a *fact of culture*, expressed in mechanisms that are themselves nothing more than an *explainable fact of nature*. In a celebrated text in "Principles of Philosophy," Descartes writes, "It is certain that all the rules of mechanics belong to physics, *to the extent that all artificial things are thereby natural*." . . . [T]hey are thus the direct or indirect products of a technical activity that is as authentically organic as the flowering of trees (Canguilhem 1992 59 original emphasis).

Autopoietic theory alone lacks the capacity to mediate and adapt cognitive interchanges external to its constituent domains; it will not, by itself, propel generative design. Therefore, to incorporate autopoiesis into research and learning systems envisioned here, nomadic (peripatetic) reach and sensory agency are required to recognize whether and/or how environments, organisms, and objects are metabolic — or in Canguilhem's (1992 59) sense, "organic as the flowering of trees" (Church & Regis 2012. Di Paolo 2005. Langton 1988. Weber & Varela 2002). Fortunately, a community of scholars has monitored and modified original autopoietic fundamentals to evolve restrictions of agency and to accredit non-conscious intelligence or sense-making in the environment (Bourgine & Stewart 2004. Di Paolo 2005. Maturana & Varela 1980. Weber & Varela 2002. Thompson 2007).

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1.1 • Grounding Theory

Reflecting upon Evan Thompson's words (2007 243): "the human mind is embodied in our entire organism and in the world," I looked to philosophies of science and scientific research — archaeology, biological theory, and cognitive science — to conceptually hybridize environmental and cognitive systems for design programs (Jonas 1965. 1966. Malafouris & Renfrew 2010. Odling-Smee et al. 2013). I did so in the context of scientific and architectural history while also considering emerging views from education (Barnett 2007. Bayne 2008. Davis 2008. 2010. Mason 2008a, b). Through this multidisciplinary consultancy, three goals were achieved:

- 1) Data, methods, and theory were examined through a survey of literatures simultaneously with the investigation of texts and projects for procedures and precedents.
- 2) Groundwork was laid for student case studies to test new data, design, and prototypes involving technology and mobile smartphone/app systems.
- 3) Demonstration methods were readied for learning, teaching, and implementing design procedures as means to cultivate research data.

External observers, agents, or students may then concurrently perform in domains of autopoiesis and extended cognition in order to bring about biological activation involving objects and environments (Clark 2013. 2014. Luhmann 1990a. Maturana & Varela 1980). Considering the architect, designer, or student as observer-agents both occupying nature and processing nature, I built autopoiesis and extended cognition into scaffolding to establish design research in a milieu of biology, technology, and nature (Clark 2008a. Di Paolo 2005. Maturana & Varela 1980. Weber & Varela 2002).

One mechanism of this hybrid results in autopoietic sense-making (intelligence) evolved to include material and place making (Di Paolo 2005. 2008. 2010). "The sense-making of living systems," according to Di Paolo is one:

... in which a situation is meaningful in terms of its consequences for the conservation of a way of life. In the living system this is ultimately the conservation of its autopoietic organization, its own survival, and viability (Di Paolo 2010 145).

Di Paolo's (2010) theoretical consideration of sense-making as a survival strategy ("conservation of a way of life") potentiates the interpretation of research performances from interchanges between autopoietic unities such as: *student + technology + environment*. More

specifically, sense-making is a process of intelligence illustrated, for example, by Turing's drawings decoding algorithmic biological functions translated into digital simulations (Chapter 5) and activated when the simulations communicate intelligent, deployable data. Turing's drawings, as autopoietic communication processes, are explained first through analogy with two Cubist paintings, one by Gerald Murphy, the other by Juan Gris (Chapter 2. 2.2), and then again later, when Clark (2008a xxv) references Richard Feynman's insistence that his notes participated in his thinking (Chapter 5. 5.4).

In terms of implementation with software and apps, sense-making as "predictive search" may be aligned with Turing's "evolutionary search" (Teuscher 2004a 500. Turing 1948) and "machine intelligence" (Langton 1988 1996) illustrating one direction AI-supplemented learning might now follow to produce metabolically responsive architectural performance (Chapter 5). Teuscher thinks of such activity in which Turing's "deeper motivation was to build structures [machines] that allow for learning" (Teuscher 2004a 500). The predictive model for autopoietic-extended design OS then might be compared to search engine operation in social media realms using machines and AI tuned to "learn" biomimetics and living technologies (Armstrong 2010. Coyne 2010. Montebelli *et al.* 2013. Spiller 2009. Webb & Consi 2001). However here, and appropriate in Clark's (2013a) sense, a predictive model for autopoietic-extended design is our brain-based environmental operation enacted through extended cognition as a "hierarchical prediction machine." Clark summarizes:

... predictive processing models promise to bring cognition, perception, action, and attention together within a common framework. This framework suggests probability-density distributions induced by hierarchical generative models as our basic means of representing the world, and prediction-error minimization as the driving force behind learning, action-selection, recognition, and inference (Clark 2013a 190).

Hybridized, autopoiesis (Maturana & Varela 1980) and extended cognition (Clark 2008a) define the observer (architect or student) as an agent who implements sense-making and prediction to recognize, investigate, and analyze properties from nature, objects, and environments (Clark 2013a. Di Paolo 2008). Maturana and Varela weigh-in with:

... every prediction is a prediction of a class of interactions. ... This makes living systems inferential systems and their domain of interactions a cognitive domain (Maturana & Varela 1980 10).

I think we may now begin to comprehend that design/architecture is bounded as a “cognitive domain” of production. In this scenario “predictive search” is germane to biological-environmental cognition — notably, it may point out relationships between organic and machine processing vis-à-vis analog and digital data consumption. Sense-making then in non-cognitive life forms — say sugar-seeking bacteria (Maturana & Varela 1987 149. Thompson 2007 157. Varela 1997 79) or light-seeking amoeba (Adamatzky 2013) — demonstrates sense-detection, directional navigation, and search routines based on organism-to-environmental prediction discussed by Clark (2013. 2013a). The message I interpret for architectural systems is that metabolic functions may be introduced through living, yet non-sentient systems such as bacteria (Armstrong 2012. Cronin 2011. Spiller 2009).

Biological performance in, say, amoeba (Adamatzky 2013. Maturana & Varela 1987 144) or in the cellular reaction-diffusion patterning explored by Turing (1952) and Richards (2013), illustrates potential components for architectural models using metabolic and/or intelligent building performance (Floreano & Mattiussi 2008). Metabolic sensing and monitoring is here considered at levels below consciousness yet still supplying bioprocessed control and development. Prediction in Google searches, Turing machines, and Clark's theory then bridges degrees of synthetic and intelligent systems (Clark 2013a. Saunders 1992. Turing 1948) searching to “find the model that fits the world and make the world fit the model” (Clark 2013 loc 34:37).

In the realms of high- and minimal-intelligence, autopoietic sense-making (Di Paolo 2005. 2010. Weber & Varela 2002) and Clark's hierarchical prediction (2013a), operating through extended cognition define a substratum for conceptual exploration of data involving metabolism and intelligent systems. This necessitates a note: data and information need to be distinguished from each other with data defined as the raw, chaotic, and perceived material used cognitively to create information. Information, in this context, is a product of species intelligence (Lettvin *et al.* 1959. Luhmann 1990 3-4. Varela 1981 45). Nevertheless, more is needed for delineating intelligence than the production of information, I suggest a rudimentary typology in which high-level intelligence is accompanied by memory, prediction, and processing, and low-level intelligence is bio-reactive (sensing, reaction/diffusion) lacking memory (Turing 1952. Varela 1979). Yet I caution, even this distinction may soon be antiquated with research emerging from plant neurobiology attempting to establish new typologies of biochemical memory I later cite (Mancuso 2010. Pollan 2013).

In Chapter 7 section 7.3, I consider Andy Clark's parity principle and its process- and data-filtering use of objects and environments for thinking. But, at this point it is useful to preview it for dialectical relationships connecting autopoiesis and extended cognition.

Essentially the parity principle is an equation filter between cognition and data in objects and the environment, Clark notes:

It is possible that sometimes at least, some of the activity that enables us to be the thinking, knowing, agents that we are occurs outside the brain? . . . [M]inds like ours are the products not of neural processing alone but of the complex and iterated interplay between brains, bodies, and the many designer environments in which we increasingly live and work (Clark 2010b).

Objects, machines, environments, and biochemistry act, among other capacities, as switching devices, activators, or inhibitors for cognitive input/output (Chapter 7) and potentially invoke the parity principle. Further, as we shall see, Turing's (1952. 1953) biological switches (Teuscher 2004 500) and activators constitute important discoveries involving biological reaction-diffusion mechanisms (Brenner 2012. Reinitz 2012) and may have been Turing's Morphogenetic steps articulating aspects of machine thinking/prediction and AI in programming (Chapter 5).

If we invoke artificial intelligence's extensive physical role, for example in Google's (2012) algorithmic searches and in self-driving automobiles as analogous to architectural infrastructures, or if we attempt to extrapolate hypothetically from Stanford University and the J. Craig Venter Institute's computational bacterium (Covert *et al.* 2012) to imagine metabolic material components (Markoff 2012. Venter 2013 142), we use cognitive devices Clark explains by means of the parity principle (Chapter 7. 7.2) to equate or not to equate environmental phenomena (Clark 2008a). And, if we seek recursive "self-organization in active living matter" (Palacci *et al.* 2013) to arrive at design situations making sense, for example, of Adamatzky's (2013) biocomputational research (computing amoeba), we are recognizing cognition, at least partially, as Clark formulates, "outside the brain," because amoeba (Protozoa) don't have brains (Clark 2008b).

My intention in highlighting AI from the *Atlantic's* portrait of Douglas Hofstadter (Somers 2013), is to emphasize that even as AI has gone mainstream, demonstrating what a few years ago would have been applauded as intelligent (Turing 1950), we have continually raised the bar to downgrade machine intelligence. I don't think anyone considers any of the digital agents listed below as actually intelligent; but they are processing and learning outside the brain as well as outside of carbon-based life:

AI pervades heavy industry, transportation, and finance. It powers many of Google's core functions, Netflix's movie recommendations, Watson, Siri, autonomous drones, the self-driving car (Somers 2013).

In parallel, Varela thinks: "There is considerable support for the view that brains are not logical machines, but highly cooperative, nonhomogeneous, and distributed networks" (Varela 1992 321). If brains are networks, as indications from neurology seems to confirm, Clark and Varela are proposing that those networks are environment/nature dependent while also phenomenologically (forcelike) extending out of the body (Clark 2008a. Markoff 2013. Nagel 2012. NIH 2013. Requarth 2013).

Therefore, by considering cognitively extended student visualization engaging objects and environments, I chart networked autonomous physical and phenomenological systems in sync with autopoietic-extended design users. Maturana and later Varela individually describe autonomous systems. First from Maturana:

A system is autonomous if the relations that characterize it as a unity involve only the system itself . . . Thus defined, autonomy can be viewed as a central characteristic of living systems (Maturana 1981 21).

And here from Varela and Bourguine:

Autonomy in this context refers to . . . [living creature's] basic and fundamental capacity to *be*, to assert their existence, and to bring forth a world that is significant and pertinent. . . . Thus the autonomy of the living is understood here *both* in regards to its actions and the way it shapes a world [including extended phenotypes] into significance. . . . Furthermore, it is by focusing on living autonomy that one can naturally go beyond the tempting route of characterizing living phenomena entirely by disembodied abstractions, since the autonomy of the living naturally brings with it the situated nature of its cognitive performances (Varela & Bourguine 1994 xi original emphasis).

Having recognized autonomy as a key characteristic in nature, I find Di Paolo *et al.* (2010) aligning autopoiesis with the concept of extended mind systems (Clark 2008a) as an autonomous and enactive "cognitive domain:"

Cognitive systems are also autonomous in an interactive sense in terms of their engagement with their environment as agents and not simply as systems coupled to other systems. . . . As such, they not only respond to external perturbations in the traditional sense of producing the appropriate action for a given situation, they do in fact actively and asymmetrically regulate the conditions of their exchange with the environment and, in doing so, enact a world or cognitive domain. . . . To view cognitive systems as autonomous is therefore to reject the traditional poles of seeing mind as responding to environment stimuli on the one hand, or as satisfying internal demands on the other — both of which subordinate the agent to a role of obedience to external or internal factors (Di Paolo *et al.* 2010 38-39).

Cognition registers sources of animate, inanimate, and environmental data — nature: plants, trees, bones, electricity, cells, natural forces, architecture — yielding phenomenological data we use in the construction of reality and knowledge (Luhmann 1990a). Hereafter, for autopoietic-extended design the environment and objects (Rowlands 2010 275) are morphologically enactive (Varela *et al.* 1992) for design learning insights and operations (Sullivan 1999. Thompson 1992).

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1.2 • Toward an OS Synthesis

The autopoietic-extended design program organizes research and biomimetic visualization for architecture under the rubric of an operating system and/or as a research protocol. I began experimental implementation by integrating selected design apps and smartphones (Fig 1, p29) with procedural methods for testing in online and university courses by developing Student Handbooks as guides, illustrations, and texts (Dollens 2012. 2014). My experience designing and teaching such courses (Appendices 1. 2), suggests that autopoietic-extended design may eventually be programmed as a smartphone app following the lead of social media sites. As a dedicated e-learning OS and protocol serving individual students and design classes, autopoietic-extended design helps organize procedures and methods for seeking biological input/output data for translation into architectural performance, visualization, materials, and structures (Figs 2-3, pp44-45). Recent tests took place at two universities in Barcelona in the spring semester, 2014 (Figs 4-5, pp47-48). In both cases the mobile learning methods native to autopoietic-extended design were overlaid onto studio-based classes and design research, making apparent ontological ways of approaching nature, technology, and the environment. This approach is then part of a model for realizing bioremedial design and theoretical interventions

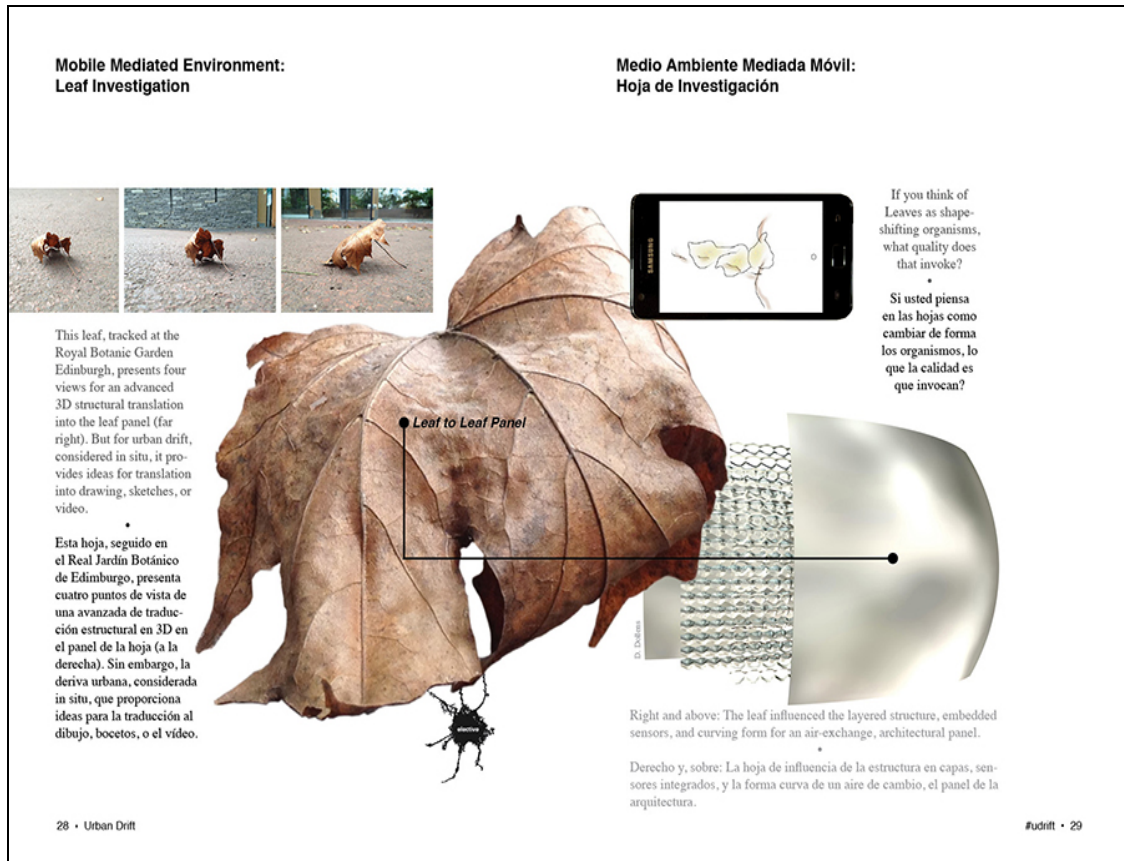


Fig 2. Leaf Investigation. Student Handbook Illustration (Appendix 1). Exercise to investigate with smartphone and apps ways of reimaging leaf forms for surface and monocoque panel development. Drawings/text: Dennis Dollens.

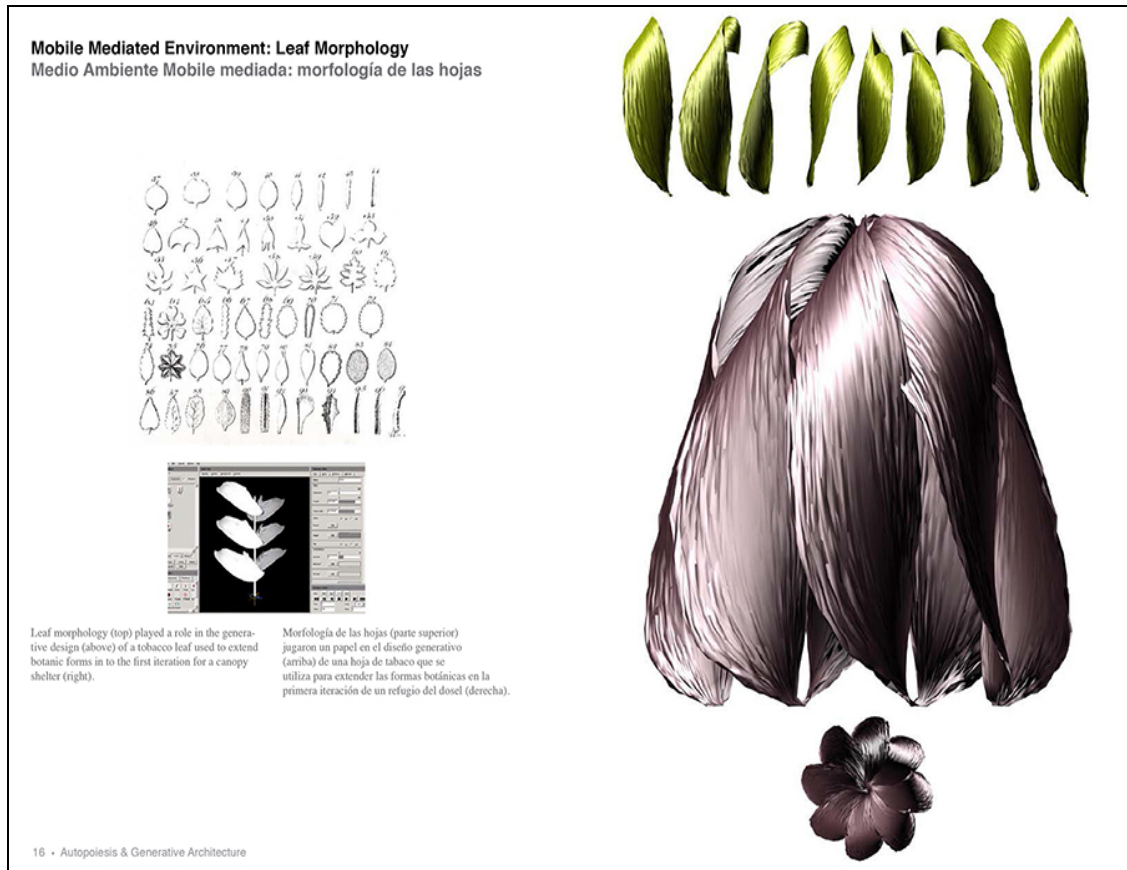


Fig 3. Leaf morphology. Student Handbook Illustration (Appendix 1). Exercise referencing botanic morphology to investigate with smartphone and apps ways of reimaging leaf forms for surface and monocoque panel development. (See also Sullivan Plates 15-19 p154-158). Drawings/text: Dennis Dollens.

that balance acts of generative design with technological acts of computation, simulation, and fabrication.

Central to the OS is the idea of bringing e-learning students or researchers into direct contact with research environments and subjects. Occupation of an urban or natural site is by means of mobile technology and physical presence enhanced with use of onsite smartphone apps enabling student-to-site-to-technology production. This collaboratively exposes student research to algorithmic design input integrating architectural experimentation, for example, with the unfolding or crinkling of a leaf (Figs 2-3, pp44-45) used as an assignment for the morphological development of shape-shifting facades or infrastructures (Focatiis & Guest 2002. Hitt 2014).

Goals, in the context of teaching research methods may be developed and organized to rigorously approach nature and biology beyond similes and biomimetic banalities such as: *this is like a flower* or *that is like a tree* to embed a logic for design and materials as well as morphological and performative analysis. Grounding the OS in an epistemological framework of syllogistic logic (Corbett 1971. Toulmin 1984) here helps to integrate theoretical precedents to set benchmarks from historic architecture, philosophy, and archival computation that conceptually, theoretically, and chronologically buttress my arguments (Chapters 4. 5). Those benchmarks derive from introductory coursework that assigns student research models demonstrating one-to-one biomimetic analysis (Appendix 1). Importantly, the benchmark exercises provide clues and connections students can follow in order to map secondary and tertiary research trajectories for coherent development over the course of a class.

To arrive at a point where preliminary research data inputs to design modeling, I articulate a developmental process; first surveying Louis H. Sullivan's (1990) morphological system for architectural ornament and his ideas for learning design (Chapter 4); second, I integrate Alan Turing's morphogenetic drawings, his algorithmic plant simulations, and his contributions to machine intelligence and theory (Turing 1950. 1952. 1953. Swinton 2004) as foundational to computational simulation and algorithmic design (Chapter 5). In these two chapters (4. 5) I create case studies for defining what is now unacknowledged generative design heritage. The lineage is further exemplified in contemporary archaeological scholarship debating issues revolving around landscapes and constructed objects (Chapter 6) considered through extended cognition (Clark 2008a. Malafouris & Renfrew 2010. Noë 2009. Thompson 2010).

After citing Sullivan's 1924 morphological learning system, I analyze Turing's (1948. 1950. 1952. 1953) work as the historical initiation of computational simulation for

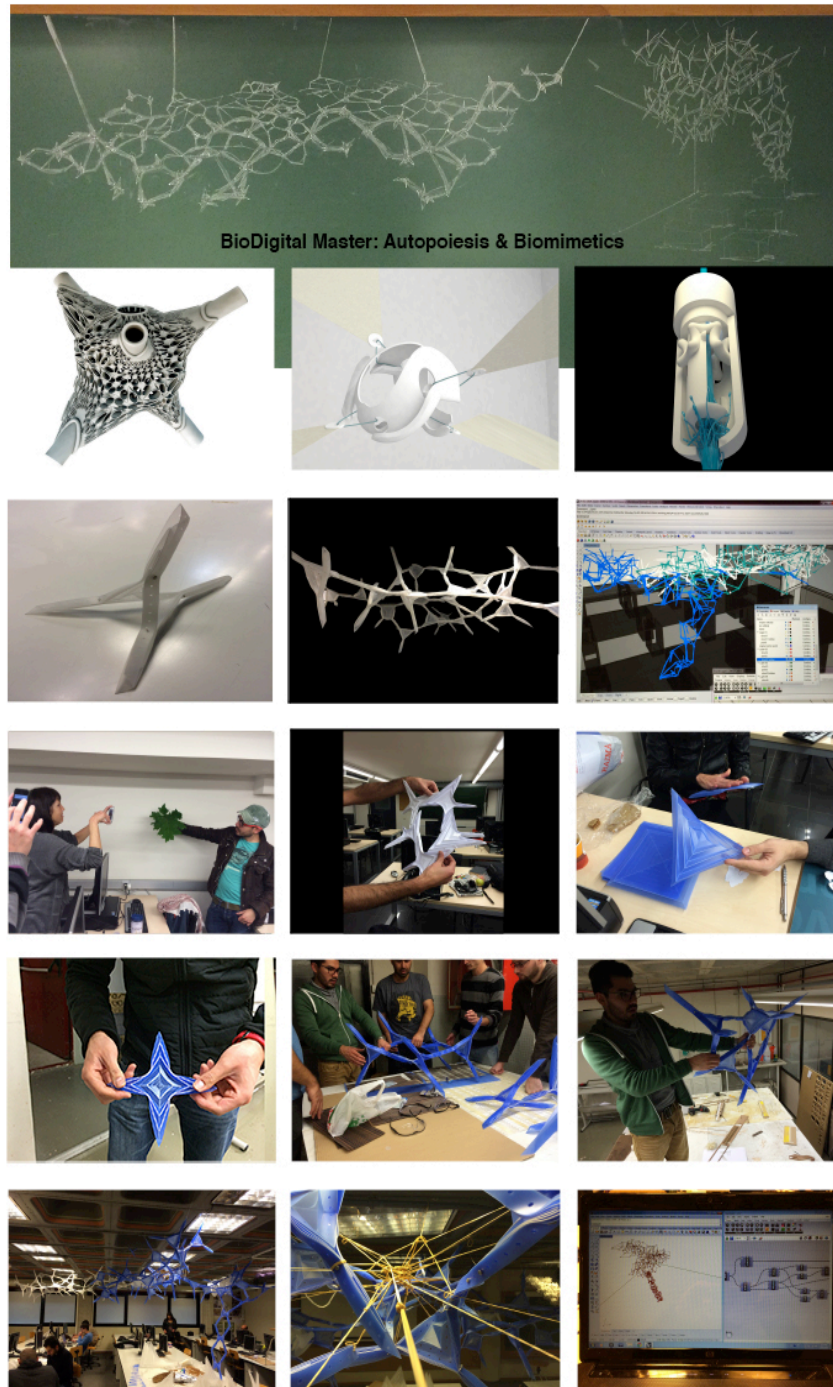


Fig 4. Implementation of principles illustrated by the Student Handbook (Appendix 1) realized by Universitat Internacional de Catalunya, BioDigital Master students in the Spring 2014 studio: Autopoietic Architecture. Dennis Dollens, tutor. Here leaf folding and morphology is investigated; folding patterns are tested on paper and then with a laser cutter on plastic sheets to evolve folding and flexing structural components. The component is then further investigated and developed for use in a flexing, spiculalike, skeletal space frame.

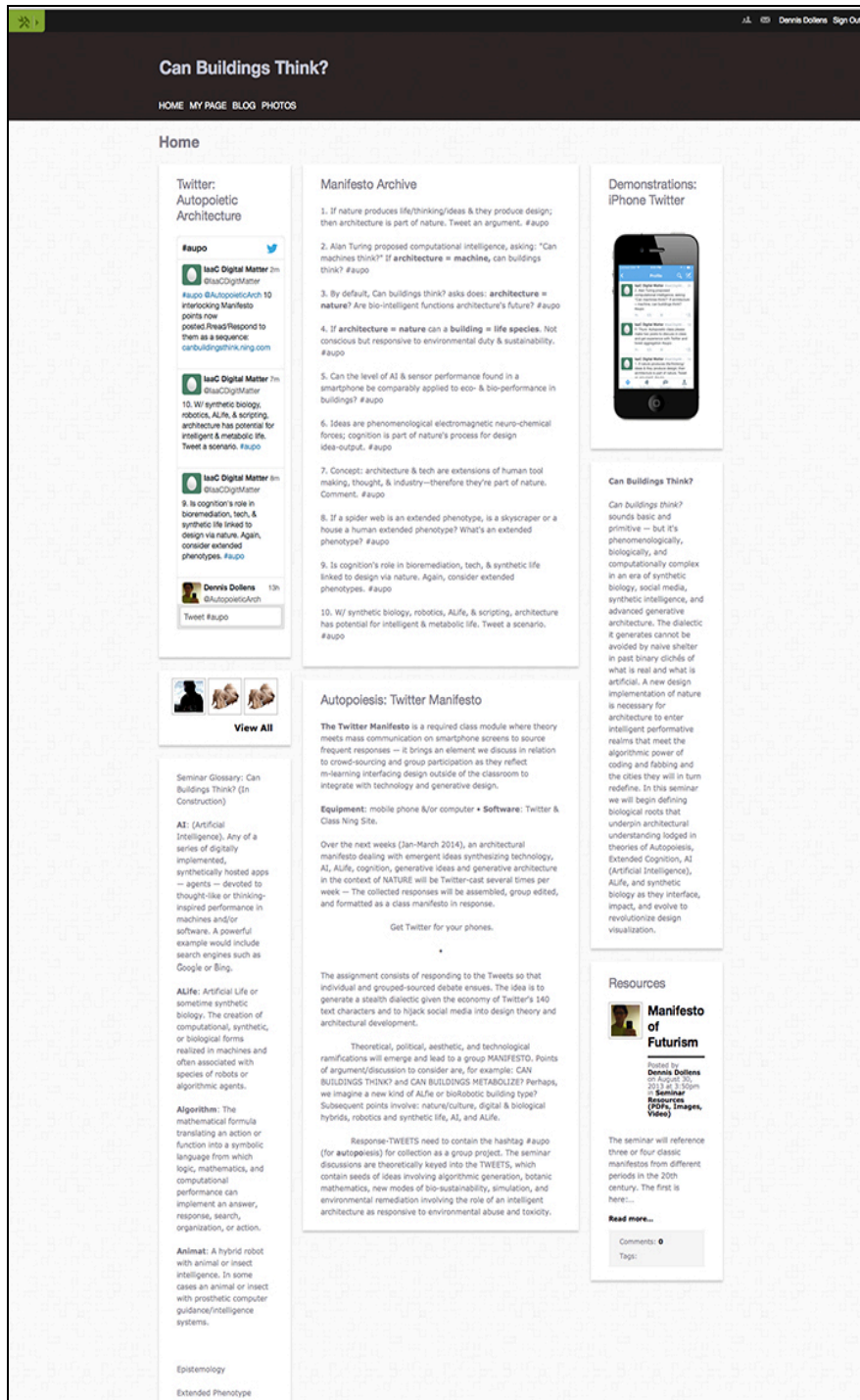


Fig 5. IAAC: Institute for Advanced Architecture of Catalonia, Barcelona, Spain. *Autopoietic Architecture: Can Buildings Think?* Spring 2014. Dennis Dollens, tutor. Screen shot of the class Twitter Manifesto website, posting and discussing biological, synthetic, and computation points for considering metabolic intelligent architecture. The manifesto points were Tweeted two or three times per week with subsequent out-of-class Twitter discussions (open only to class members and critics) with the student's texts as new or reTweets. The Tweets questioned definitions of life, intelligence, metabolism, sense-making, cognition, and consciousness as they would be used in digital design where life properties and attributes play a role in architectural performance. (See Appendix 2 for manifesto Tweets #1-14).

architecture later coded through L-systems (Floreano & Mattiussi 2008. Lindenmayer 1968. Lindenmayer & Prusinkiewicz 1988. Prusinkiewicz 1994. 2004. Swinton 2004). For a rule-of-thumb definition of simulation, I look to Michael Hensel: "simulation is the mathematical representation of the interaction of real-world objects" (Hensel 2006 10). I also register in a design context, Turing's (1952) contribution to intelligent systems and biological, botanic, and embryonic simulation (Teuscher 2004). I am therein formulating a program for research, teaching, and learning — the OS — to methodologically invoke technological investigation and firsthand visualization of nature. Through such a process I suggest that asking, Can buildings think? be rephrased as, *Why aren't buildings thinking?*

So, while attributing Turing's biological simulations as an origin point for generative architecture, I recognize they were earlier a harbinger of synthetic biology and synthetic life. In a late-2013 article for *Foreign Affairs* Laurie Garrett wrote a nuanced portrait factoring in ethical ecology, public safety, and politics in: "The Promise and Perils of the Synbio Revolution." Garrett wrote of a new generation of biologists:

... taking over the frontiers of science — a breed that views life forms and DNA much the way the technology wizards who spawned IBM, Cisco, and Apple once looked at basic electronics, transistors, and circuits. These two fields, each with spectacular private-sector and academic engagement, are colliding, merging, and transforming one another, as computer scientists speak of "DNA-based computation" and synthetic biologists talk of "life circuit boards." The biologist has become an engineer, coding new life forms as desired (Garrett 2013).

Prompted by Garrett's "life circuit boards," I invoke one primary computational connection that today bridges living and inert, biological and synthetic. I use the broad reading of algorithm (Langton 1996) as a procedural set of directions between direct observation of nature, computation, and generative design and therefore common between conscious and non-conscious organisms and machines. Algorithm, between Turing's simulations and drawings, implicates genotype, phenotype, and extended phenotypes expressed mathematically as machine- and morphogen-capable of enacting life or lifelike functions (Turing 1948. 1951. 1952. 1953). In effect, capable of aligning rule-sets involving autopoiesis and extended cognition in digital representations (Thompson 2007. McMulling & Varela 1997. Uribe 1981. Varela et al 1974). I turn to Christopher Langton's classic AI and A-Life research: "The essence of an algorithm is the notion of a finitely specified, step-by-step procedure to resolve a set of inputs

into a set of outputs" (Langton 1996 345). I also follow Langton by introducing algorithm into biology and autopoiesis with the understanding that:

In the context of Artificial Life, we need to generalize the notions of *genotype* and *phenotype*, so that we may apply them in non-biological situations (Langton 1988 22 original emphasis).

And, in the context of autopoietic-extended design, aiding exploration of metabolic life and AI expressed in genotypes and phenotypes, we need a strong view of extended phenotypes:

Some aspects of phenotype are expressed beyond the limits of the bodies of the organisms that are responsible for them. To draw attention to this, Dawkins (1982) coined the term extended phenotype. Although some of these phenotypic effects may be large both in terms of their impact on the organism itself and on the surrounding environment, others may be very small. To avoid devaluing the whole concept Dawkins (1982), while making clear that any alteration of the environment beyond itself is an extended phenotypic effect, suggests that in practice the concept should be confined to those effects that can be shown to alter the fitness of the organism responsible for them. Beaver dams and gopher burrows may be obvious examples of extended phenotypes, however, Dawkins (1982) makes clear that his definition also embraces quite different phenotypic effects, for example, the manipulation by parasites of the physiology and behavior of their hosts (Hansell 2005 194).

In order "to generalize the notions of *genotype* and *phenotype*" (Langton 1988 22) and theoretically situate metabolic architecture consistent with extended phenotypes and open to input/output, I looked to Arturo Rosenblueth, Norbert Wiener, and Julian Bigelow's foundational cybernetic paper, "Behavior, Purpose, and Teleology:"

By output is meant any change produced in the surroundings by the object. By input, conversely, is meant any event external to the object that modifies this object in any manner (Rosenblueth *et al.* 1943).

Finally, looking now to the point where Weber and Varela (2002) and Di Paolo (2005) reconstitute autopoiesis, I subscribe to teleology (divorced from theology) as formulated for

autopoietic sense-making; here I use Thomas Nagel's (2012) "natural teleology" encapsulated in *Mind and Cosmos*:

I am drawn to . . . natural teleology or teleological bias, as an account of the existence of biological possibilities on which natural selection can operate (Nagel 2012 91).

And:

. . . The teleology I want to consider would be an explanation not only of the appearance of physical organisms but of the development of consciousness and ultimately reason in those organisms (Nagel 2012 92).

With Nagel's teleological option "reason in those organisms" and their consequence in his theory (parallel with matter and energy), he asks:

. . . would an alternative secular conception be possible that acknowledged mind and all that it implies, not as the expression of divine intention but as a fundamental principle of nature along with physical law? (Nagel 2012 22).

In my developing context, where architecture is posited nondualistically as part of nature, extended cognition (Clark 2008a) and autopoietic sense-making (Di Paolo 2005. Weber & Varela 2002) may confront issues of evolved cognition from which tool and shelter making were manifested — cognitively as well as physically extended — after eons of evolutionary steps (Hansell 2005. Herrmann 1984. Langton 1988. Malafouris & Renfrew 2010. Nagel 2012. Rieffel *et al.* 2013). Those stepped constructions resulted in agent-as-biomachine (Canguilhem 1992. Clark 2008a) in the domain of an organism's self-production (teleological) drive to maintain homeostasis (Maturana & Varela 1980). Through that homeostatic process, I situate architecture as a tool-machine — extended phenotype — evolving toward living technology (Bedau *et al.* 2010. Herrmann 1984. Jonas 1966. Odling-Smee 1996) (See "machinic" Chapter 5. 5.2).

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1.3 • Autopoiesis to *Animate Life*

The text-of-record here is *Autopoiesis and Cognition: The Realization of the Living* by Humberto Maturana and Francisco Varela (1980). From it I consider Maturana and Varela's theory as compatible with extended cognition (Dollens 2014. Floreano & Mattiussi 2008. McMulling &

Varela 1997. Maturana & Varela 1980. Turing 1948. 1950. 1954. Wolfram 2002). My scenario foreshadows an autopoietic reading focused in a living technological, environmental, and biocomputational context of design research (Clark 2001b. 2005. 2008a. Copeland & Proudfoot 2004 335. Di Paolo 2005. Jonas 1965. 1966. Weber & Varela 2002).

In this lineage, I sense Turing's shadow in the background, generating autopoietic input (to my mind logically so), while distant echoes of his work reverberate in discussions of extended mind. Maturana and Varela in their way, and Clark and Turing in theirs, foresee or foresaw biological and mechanical hybridization. After all, one of Clark's books is titled *Natural Born Cyborgs* (Clark 2003), an earlier title is *Mindware: an Introduction to the Philosophy of Cognitive Science* (Clark 2001a), while his current research investigates cognitive prediction (Clark 2012. 2013. 2013a). And Turing (Chapter 5) may be credited with the first biological/botanic simulation (Swinton 2004. 2013) that, as John Reinitz (2012 464) wrote in *Nature*: "is possibly the first openly published case of computational experimentation."

By considering dawn-of-digital algorithmic modeling of life, I concluded that Varela, Maturana, and Uribe (1974) attempted to code autopoietic life (Uribe 1981. Varela 1979). I found their cellular automata (recreated: McMulling & Varela 1997) ties historic research and current interest between computation, synthetic biology, and metabolic life (Maturana & Varela 1980 82-83) together with Turing via computer simulation, programming, and computational biology (Gardner 1970. Ray 1994. Uribe 1981). Varela described their project:

One of the specific contributions of the study of self-organizing mechanisms — of which autopoiesis is a specific instance — is that the traditional opposition between the component elements and the global properties disappears. In the simple example of the cellular automaton . . . it is precisely the reciprocal causality between the local rules of interactions (i.e., the component rules, which are akin to chemical interactions) and the global properties of the entity (i.e., its topological demarcation affecting diffusion and creating local conditions for reaction) which is in evidence. It appears to me that this reciprocal causality does much to evacuate the mechanist/vitalist opposition and allows us to move into a more productive phase of identifying various modes of self-organization where the local and the global are braided together explicitly through this reciprocal causality. Autopoiesis is a prime example of such dialectics between the local component levels and the global whole, linked together in reciprocal relation through the requirement of constitution of an entity that self-separates from its background. In this sense, autopoiesis as the characterization of the basic pattern of the living does not fall into the traditional extremes of either vitalism or reductionism (Varela 1997 78).

The digital/analog crossover, modeling and exploring traits of life in code and silicon also highlights a biodigital track forking in one direction to become digital botany or environmental simulation (Bentley 2001. Floreano & Mattiussi 2008. Ray 1994) and, in another direction to become generative architecture incorporating both (Deussen & Lintermann 2010. Dollens 2014. McMulling & Varela 1997. Varela *et al.* 1974).

Biological theory from Maturana and Varela (1980. 1987) compiled with examples of Turing-inspired machine coding from botany and embryology (Dollens 2014. Richards 2013. Swinton 2004), networked through Clark's (2008a. 2013) cognitive-agent environmental hybrid is an innovative scaffold for biodigital learning and research. This scaffold supports technology as an aspect of life-factoring metabolism so that architectural functions are situated as part of nature via autopoietic-extended design (Clark 2008a. 2013. Dawkins 1988. Langton 1988. McMulling & Varela 1979. Ray 1994. Turing 1952). In this hybrid, I organize theory as multi-authored, multidisciplinary processes evolving OS protocols for design research. To reflect the above through contemporary architectural criticism, I draw upon Michael Hensel's, *Techniques and Technologies in Morphogenetic Design*:

What can be learned from these new methods is not only new sensibilities relative to the visualized processes, but also the specific configurations and features of the tools and their potential contributions in rethinking approaches to design that aim for instrumentalizing self-organization (Hensel 2006 13).

Autopoiesis is widely considered the classic theory of biological self-organization used here to identify living systems (Di Paolo 2010. Guattari 1995. Luhmann 1990. Thompson 2007 60. Weber & Varela 2002 116). To this consideration, Eric Karsenti frames self-organization, first tracking it to Kant's definition of a characteristic for living systems and then finding a modern simpler definition where:

... dynamic organization emerges from the collective behavior of "agents," the individual properties of which cannot account for the properties of the final dynamic pattern (Karsenti 2008).

Subsequently, I read Hensel's (2006) proposed "instrumentalizing" of self-organization as a mediator and data filter when placed within the context of autopoietic-extended design. The deployment of autopoiesis (as instrumentalizing) to the end Hensel (2006) discusses is here an

objective in specifying “configurations and features of the tools and their potential contributions.” That categorization, in alliance with students, architecture, and technology is recursively factored in autopoietic-extended design via complexity, emergence, and self-organization in forthcoming chapters (de Duve 2003. Fenwick *et al.* 2011. Hensel 2006. Mason 2008a. b. Thompson 2007).

Viewed from my perspective, the scaffolding to support autopoietic-extended design includes as structural bracing: biomechanical, biosynthetic, and algorithmic processes vis-à-vis Turing's (1936. 1948. 1950. 1951. 1954) intelligent machines and morphogenetic research, as well as, notably, his computational-botanic drawings (Chapter 5). The concatenations above, lead to recasting questions for architecture that were originally asked of machines more than sixty years ago. Turing (1950) famously asked: "Can machines think?" (Dennett 1998. Saunders 1992). Specifically, two Turing-derived questions then emerge for generative architecture:

- 1) Can buildings think?
- 2) Can buildings metabolize?

These are generative questions — iterative — and I return to them periodically, asking them in different contexts, posing them in reference to theoretical autopoiesis and extended cognition's input and output as they might inform generative design (Maturana & Varela 1980. Clark 2008a). As generative questions, their biosystemic provocations propel the study of procedures for technologically integrated design research and theoretically attuned synthesis of the biological and phenomenological environment.

My inquiry into potential metabolic and/or intelligent architecture then constitutes branched networks for research and investigation conducted through autopoietic-extended design. That formwork supports the OS for in-field design learning open to questions of machine intelligence interfacing animate/inanimate systems; support also sources nature as it influences building performance. Case studies, literature reviews, as well as narrative experimental design practice further sustain and demonstrate the OS propositions as the thesis progresses.

Program rootstock for intelligent bioarchitecture then grows from metabolic life as outlined by Maturana and Varela (1980) as well as from cognition-to-environmental communication and prediction hypothesized by Clark (2008a. 2013). Turing's conceptualization of intelligent machines and his ways of visualizing nature in computation and drawings (Chapter 5) counterbalance both autopoiesis and extended cognition (Clark 2008a. Maturana & Varela 1980. Saunders 1992. Swinton 2004. 2013. Teuscher 2004 499. Turing 1936. 1951. Wells 2004. 2006).

While I devote Chapter 5 to Turing and the critical discussion of establishing machines and architecture as parallel systems, I now note that Turing articulated, for a general audience, a characteristic of his Universal Turing Machine in a 1951 BBC broadcast. That articulation sent notice that he had ideas of operational intelligence in computational machines and, as we see in other contexts, he had started to contemplate (Turing 1951a) digitally computing those ideas as actions from nature, expressed for example in embryology (Richards 2013) while also pondering brain simulations (Cooper & van Leeuwen 2013. Copeland 2012. Hodges 1992. Teuscher 2004).

In his under-cited BBC Radio transcript (Turing Digital Archive 2014), Turing qualified what has confused many readers since 1936. Their confusion arose, and in the popular press still arises, from the term *universal computer* (Hodges 1992 441. *Nature* 2012. Turing 1936. 1951). His 15 May 1951 broadcast clarified that Turing did not mean that his theoretical computer (1936) could be:

... a bulldozer or a steam-engine or a telescope, but [that it could] replace any rival design of calculating machine (Turing 1951 2).

He explained that his machines could *universally* emulate other machines in parallel, computational categories (Chapter 5).

By the time of the BBC broadcast, Turing had designed and established programmable machines (computers) and devised roles for what we now call software applications or apps (Copeland 2012. Hodges 1992). He had also written the first programming handbook for Manchester's computer and its 1951 code known as "Scheme A" (Cooper & van Leeuwen 2013. Copeland 2012. Dyson 2012. 2012a. Richards 2005. Teuscher 2004. Turing 1936). The handbook taught programming demonstrating how to code a universal machine in order to run different programs, not by physically reconfiguring the computer, as had been the standard of the day, but by loading into its memory a discrete program. If today I work with a desktop computer, laptop, tablet, or smartphone, I work with a universal Turing machine running dedicated apps (Copeland 2012. Dennett 1998. Langton 1988).

For an insight into expectations of intelligent machines, Turing's BBC broadcast seeded a popular understanding of computers as programmable and algorithmically responsive (Bedau *et al.* 2010. Copeland 2012. Langton 1996. Turing 1936. 1948. 1950. 1951. Wolfram 2002). Turing's radio talk opened conceptual lines through which listeners might consider how machines could, potentially, be categorized as thinking and generative (Turing 1950. 1953) — after all they were frequently referred to as electronic brains by the British press. Hodges (1992

349) tells of Sir Charles Darwin, Turing's boss at NPL (National Physical Laboratory) and the grandson of Charles Darwin, addressing the radio program "The Listener" on 14 November 1946 with expectations that Turing's machine from "Computable Numbers" (Turing 1936) would be built:

Turing, who is now on our staff, is showing us how to make his idea come true (Darwin 1946 in Hodges 1992 349).

Considering architecture in the league of large machines with internal functions keeps buildings parallel with Turing machines and avoids immediate theoretical collision with human consciousness and sentient attributes I do not advocate when asking: Can buildings think? I recall Evan Thompson recapping John Searle: "conscious states are biological processes" (Thompson 2007 238), and I heed the association referenced in Di Paolo's (2010) words below. To be clear, I am considering instances of biological, biomechanical, and even biorobotic/biosynthetic life for buildings; but I am not thinking of that species of life/metabolism as conscious in a human sense (Stewart 1995 318).

To this end I avoid ascribing any one-to-one, organism-to-building attributes, yet some of Di Paolo's discussions of intelligence for robots cause me to think that if architecture were classified as biorobotic, then, by direct analogy, buildings could assume the role of evolving intelligent agents — they could learn algorithmically (D'Andrea 2013). To begin with, Di Paolo contends:

We can ascertain beyond any shadow of a doubt that organisms have an identity beyond the epistemological convenience of detached ascription. In living systems "nature springs an ontological surprise in which the world-accident of terrestrial conditions brings to light an entirely new possibility of being: systems of matter that are unities of a manifold, not in virtue of a synthesizing perception whose object they happen to be, nor by the mere concurrence of the forces that bind their parts together, but in virtue of themselves, for the sake of themselves, and continually sustained by themselves" (Jonas 1966 79 quoted by Di Paolo 2010 138).

Regarding a building as an intelligent agent in the environment, but one lacking humanlike consciousness or agency, there is no obstacle to considering it, by analogy, with Turing machines extended through computation, programming, and biorobotics. After all, robotics, AI, ALife, synthetic biology, and living technology (Bedau 2003. Bedau *et al.* 2013) are

conceptually years ahead of architecture in developing environmental intelligence as active and reactive systems. And, Di Paolo provides the mechanism for contemplation:

The way we know this [identity/intelligence] for certain is simply that we are organisms. We know by the direct availability of our bodies and experience and by our struggles and concerns that we are indeed one of these entities (Di Paolo 2010 138).

By posing the question, Can buildings think? at a time when technology is introducing synthetic life, micro- and nano-robotics, learning algorithms, and non-human variants of intelligence, we extend discussion across materials and systems, thereby leading to larger questions of what generative architecture is? (D'Andrea 2013. Frazer 1995. Hensel *et al.* 2010. Lynn 1999. Markoff 2014. Spiller 2009. Turing 1950. Venter 2013. Webb 2009). If we can think environmentally — and if environments, in a manner of speaking, communicate outside of human communication (Brenner *et al.* 2006. Mancuso 2010. Mousavi *et al.* 2013), and if algorithmic machines, in another manner of speaking, simulate thinking — we should investigate how to teach thinking about metabolic building design (Jonas 1966. Odling-Smee 1996. Odling-Smee *et al.* 2013). Margaret Boden took on this line of thought when she attempted to distinguish three categories of ALife in combination with categories of metabolism in, "Is Metabolism Necessary?" (Boden 1999. Ray 1994).

I consider non-conscious biological intelligence in environmental performative communications possible for architectural intelligence as relational to suspected plant biochemical memory (Gagliano *et al.* 2014), chemical and electrical signaling (Christmann & Grill 2013. Mancuso 2010. Mousavi *et al.* 2013), and to *Euplectella aspergillum* (Wikipedia 2013e), an animal (sponge) of no known intellect, but capable of metabolic sense-making (Di Paolo 2005. 2010). Di Paolo points out how complex functions from organisms could be inspirational, nevertheless until the robot or building is developed with a *self*, even minimally specified as in bacteria, it cannot deal with a "space of *meaning*:"

My contention . . . is that robot design may be getting important inspiration from the properties of biological neuronal mechanisms and from the dynamics of animal bodies, but it is getting little or no inspiration from the fact that the organisms that serve as models are *living systems* and . . . they structure their activities and their environment in a space of *meaning* defined as the distinction between what is relevant and what is irrelevant to the organism's continuing mode of existence and ultimate survival (Di Paolo 2010 134 original emphasis).

Above, as with Clark's (2008a) emphasis on environmental partnership, Di Paolo's (2010) "space of meaning" recognizes environment-to-cognition participation of the organism. Autopoietic-extended design is likewise intended to recognize and help students generate *inspiration* from the environment, organisms, objects, and nature — to identify types of intelligent behavior and invest it in prototype designs. From firsthand and technologically aided observation and onsite occupation, students survey *spaces of meaning* and/or *organisms of meaning* to generate data for design (Dawkins 1982. Odling-Smee *et al.* 2013. Turner 2000).

In the lineage of Turing's (1936. 1948. 1950. 1952) machines, computation, and morphogenetic research, an experimental branch of generative architecture might explore metabolic functions migrated from life-to-machines-to-buildings that update design research following Di Paolo (2010 134) where buildings, "structure their activities and their environment in a space of *meaning*" (Frazer 1995. Spiller 2009. Spiller & Armstrong 2011. Swinton 2004. Turing 1950. 1954). In this search for spaces of design meaning I also consider Thompson's (2007 140) claim that "life is an emergent order of nature that results from certain morphodynamic principles, expressly those of autopoiesis" (see also Varela & Frenk 1987).

From emergent-life pedigree, the autopoietic unity *agent + nature + design + computation* embodies Maturana and Varela's (1980 83) assertion that life will eventually be constructed (Chapters 1. 1.3 & 5. 5.2). With emergent living technology and current synthetic biology (Bedau *et al.* 2010. 2013. Venter 2012), it seems without a doubt that life will be (or has been) constructed. That feat implicates (or shall implicate) other constructions such as generative architecture in a *machinic phylum* (below). And, those implications may be, in qualified and specialized modes, experimentally prototyped as morphologically and metabolically responsive buildings, materials, and theories (Church & Regis 2012. Wallis 2013). Note Deleuze and Guattari's hybridlike coinage:

... the *machinic phylum* is materiality, natural or artificial, and both simultaneously; it is matter in movement, in flux, in variation, matter as conveyor of singularities and traits of expression (Deleuze & Guattari 1987 409).

By organization, autopoietic-extended design subscribes to the category of hybridization, adaptation, and selection Deleuze and Guattari outline, here fusing orders of student research and learning with design adaptation involving morphology, biomimetics, and cognitive phenomenology. Data sourcing supported by smartphone functionality is then aided with technology-enhanced selection and adaptation implemented (via apps and instruments)

for data analysis directed to metabolic (perhaps intelligent) systems and sensory abilities for buildings. I therein anticipate student research providing input/output data integrating morphological, metabolic, and bioremedial tasks from which to challenge existing architectural learning in biodigital-metabolic domains of generative architecture.

Defined in Evan Thompson's *Mind in Life*: "morphology comprises the bodily structures of limbs, organs, regulatory system, brain structures" (Thompson 2007 236). For Rolf Pfeifer and Josh Bongard:

Morphology includes the shape of the body, the kinds of limbs and where they are attached, the kinds of sensors (eyes, ears, nose, skin for touch and temperature, mouth for taste) and where on the body they are found (Pfeifer & Bongard 2006 2).

I follow Thompson, Pfeifer, and Bongard until their descriptions require revision for non-human systems — plants, bacteria, viruses — and, more challengingly, for AI, synthetic life, and living technology (Bedau *et al.* 2013. D'Andrea 2013). At that point, Varela and Frenk's (1987) research on "extracellular matrices" (ECM) as infrastructures — what they call "morphocycles" (1987 79) — offers an expanded perspective useful to computational simulation. Varela and Frenk:

... argue why the continuity (or global interconnectedness) of the ECM [extracellular matrices] should be brought into the foreground as an essential key to the understanding of biological form (Varela & Frenk 1987 76).

By doing so Varela and Frenk provide an alternative structural organization — the molecular matrix — capable of supporting living technology (Bedau *et al.* 2013) biointelligent architecture will require.

Elaborating related morphological and generative concerns seeded in *Folds, Bodies & Blobs: Collected Essays* (1995), Greg Lynn's (1999) *Animate Form*, adapted a view of D'Arcy Thompson's (1992/1917) morphological research and directed it to architecture for implementation. Lynn's insights into morphological change equally apply here in relation to biological and bioalgorithmic design research as they meet metabolism and intelligence. As we shall see, *Animate Form*'s concerns project beyond Sullivan's *System* (Chapter 4) into digital animation and photographic and videographic analysis appropriate to autopoietic-extended design. In D'Arcy Thompson's techniques (Menges & Ahlquist 2011 32-41), Lynn found

examples of morphological development relevant to *Animate Form* and his investigations into generative architectural systems:

Scottish zoologist Sir D'Arcy Thompson analyzed variations in the morphology of animals using deformable grids, which yielded curvilinear lines due to changes in form. He compared the curvatures of deformations in formal configurations to the curvatures of statistical data, such as speed, temperature, and weight. Thompson was one of the first scientists to notate gradient forces (such as temperature) through deformation, inflection, and curvatures (Lynn 1999 26).

Lynn established digital techniques consistent with morphological data processed as "gradient forces" where living systems are read for generative data. Redeploying historical and computational practice such as those developed by Lynn or even Thompson, are here adaptable to smartphone/apps and an autopoietic-extended design practice. Lynn noted: "contemporary animation and special-effects software are just now [1999] being introduced as tools for design rather than as devices for rendering, visualization, and imaging" (Lynn 1999 11). "Gradient forces" and "generative fields" are lesson topics to consider and extend from *Animate Form* and *Folds, Bodies & Blobs*. Incorporated into a new OS-based pedagogy, procedures evolved from Lynn, may now help students simulate digital data from nature as visual, cognitive, morphological, and algorithmic feedback. In 1995 Lynn recognized, in relation to his design for the Cardiff Bay Opera House, that:

Organisms are not attributed to any ideal reduced type or single organization; rather, they are the result of dynamic non-linear interactions of internal symmetries with the vicissitudes of a disorganized context. These contexts become "*generative fields*" once they are organized by flexible and adaptable systems that integrate their differences in the form of . . . [data] . . . constraints (Lynn 1995 69 original emphasis).

With morphology historically referenced in Chapters 3 and 4 affecting ontological research methods and thus *gradient forces* and *generative fields*, I justify searching recent design history for participation in experimental autopoietic-extended design. The spectrum of contemporary and historical examples I cite are later mapped to research methods for onsite student occupancy as pedagogical practice (Appendix 1). These research sites complement student occupancy with recursive data flows, gradient forces, generative forces, and affordances (Gibson 1986) referencing history, machines, and nature (Canguilhem 1992). They take cues

from not only Sullivan (Chapter 4) or Le Corbusier (2. 2.1) but also Lynn (1995. 1999. 2006) and Heumann (2013). The research sites chosen by students thus foster performative feedback for systems of architectural intelligence and/or morphology — but, again, not humanlike thinking or consciousness (Turing 1951. Wells 2004. 2006). Autopoietic-extended design then recognizes Greg Lynn's (1995) "generative fields" recursively to understand and unify Maturana and Varela's (1980) autopoiesis across physical sites, forces, and objects (Clark 2008a) with animate and algorithmic properties recognized as defining metabolically generative architecture:

... living systems [read animate architectures] are machines, that they are physical autopoietic machines is trivially obvious: they transform matter into themselves in a manner such that the product of their operation is their own organization. However, we deem the converse is also true: a physical system, if autopoietic, is living (Maturana & Varela 1980 82).

Eighteen years after Maturana and Varela's above text, Langton discussed the animation of machines from a comparable perspective of ground-up self-organization while making complexity explicit:

... *living organism are nothing more than complex biochemical machines*. However, they are different from the machines of our everyday experience. A living organism is *not* a single, complicated biochemical machine. Rather it must be viewed as a large *population* of relatively simple machines. The complexity of its behavior is due to the highly nonlinear nature of the interactions between all of the members of this polymorphic population. To animate machines, therefore, is not to "bring" life to a machine; rather it is to organize a population of machines in such a way that their interactive dynamic is "alive" (Langton 1988 original emphasis).

In *Life at the Speed of Light*, Venter (2013) frequently refers to biological machines. In one example, he cites plants, algae, and bacterial photosynthesis:

Light-absorbing pigment is the secret of one of the most important *machines* of all, the one that drives the living economy of the oceans and surface of the planet (Venter 2013 loc 625 emphasis added).

In aggregate, the previous three quotations perform conceptual heavy lifting while continuing to support the bottom-up organization of "a population of machines in such a way that their interactive dynamic is 'alive'" (Langton 1988) in the way "a physical system, if autopoietic, is living" (Maturana & Varela 1980 82). Discussing Turing's thinking machines and their coded programming as evolutionary stages preparing for the integration of autopoietic systems with intelligent and/or metabolic architecture, Maturana and Varela (1980) and Langton (1998) provide a theoretical datum and the crux for a new design order while Turing (1936. 1948. 1950. 1952. 1953) provides fundamental computational procedures for simulation.

Furthermore, all three above quotations impose criteria that intelligent machines, as architecture, must answer to in order to be considered in metabolic roles leading to living attributes and intelligence (Langton 1988 Menges & Ahlquist 2011). With the above theoretical operations illustrating lines of thinking used in autopoietic-extended design — machinic and algorithmic computation annexes AI and data-sensed-in-nature as engines (e.g. smartphones) for design inspiration (Bedau *et al.* 2010. Floreano & Mattiussi 2008. Frazer 1995. Langton 1996. Wolfram 2002).

In hindsight, Maturana and Varela's autopoiesis furthers Turing's research metaphorically sparing his research the burdens a biologist might have self-imposed on his morphogenetic project. The two Harvard trained, Chilean scientists supplied a theoretically feasible conceptualization and discussion of autopoiesis (Maturana & Varela 1980) and Varela (1979 20-21) articulated digital autopoietic and living systems (Varela 1979 20-21) that I speculate, (perhaps unbeknownst to them) gestated in Turing's earlier papers (1950. 1952. 1953) dealing with biology, simulation, and computation. I cite Ezequiel Di Paolo's warning because it recognized the need for autopoiesis itself to evolve:

... the theory of autopoiesis in itself should be critically assessed and, if necessary, reinterpreted or extended. ... It is a mistake to take the theory of autopoiesis as originally formulated as a finished theory (a trap that is easy to fall into because of the way the theory is presented in the primary literature) (Di Paolo 2009).

I approach autopoiesis for generative architecture by keeping in mind Turing's observational and computational drawings (Chapter 5) considered through Maturana and Varela's theory (appended by Di Paolo) as it functions for biodesign thinking (Copeland & Proudfoot 2004. Di Paolo 2005. 2008. 2010. Prusinkiewicz & Lindenmayer 1990. Saunders 1992. Swinton 2004. 2013). Although, Turing never claimed his work was living, he theoretically argued that machine-thinking was possible (1948. 1950. 1951). Maturana and Varela later

articulated metabolic conditions for life and cognition, attempting at one point to build a cellular automata to test aspects of autopoietic living behavior in a digital environment (McMulling & Varela 1997. Varela *et al.* 1974). In considering algorithmic machinic life a reasonable possibility, Varela *et al.* (1974) and Uribe (1981) blurred divisions between organic, synthetic, living, and thinking operations while also supporting the eventuality that life will be constructed (Garrett 2013. Maturana & Varela 1980 82-83). Therein stands autopoietic theory's affinity with Turing's machines and embryological programming (Cooper & van Leeuwen 2013. Richards 2013) as foresight and experimentation on the way to living technology (Bedau *et al.* 2013) and, as a model for generative architecture following autopoietic-extended design.

Revealing points of unity between Maturana, Varela, Di Paolo, and Turing, I construct a habitat for autopoietic-extended design in which computational nature is traceable from Turing (1936. 1950. 1952. 1953) and the ongoing development of algorithms, AI, and ALife (Adamatzky 2013. Bedau 2003. Bentley 2001. Deussen & Lintermann 2010. Langton 1988. Lindenmayer 1968. Prusinkiewicz & Lindenmayer 1990. Teuscher 2004. Uribe 1981. Veen & Lindenmayer 1977). This habitat shelters self-organizing (but nurtured) ideas and visualizations that result in graphic and digital output — and, ultimately, in generative learning and research programs looking to metabolic and computational simulation (Bentley 2001. Deussen & Lintermann 2010. Floreano & Mattiussi 2008. Swinton 2004. 2011. Wolfram 2002). Understanding this development, Langton's distinction of ALife from biology proves basic to generative design research:

Whereas biology has largely concerned itself with the *material* basis of life, Artificial Life is concerned with the *formal* basis of life. Biology has traditionally started at the top, viewing a living organism as a complex biochemical machine, and worked *analytically* downwards from there Artificial Life starts at the bottom, viewing an organism as a large population of *simple* machines, and works upwards *synthetically* from there — constructing large aggregates of simple, rule-governed objects which intersect with one another nonlinearly in the support of lifelike, global dynamics (Langton 1988 2 original emphasis).

Some of the Maturana, Varela, Di Paolo, and Turing lessons emerging here demonstrate that cultivating complex systems (Fenwick *et al.* 2011. Mason 2008a. b) with bottom-up observation and research conducted through direct and technological observation is pedagogically reproducible. Even with cultivation, knowledge construction hinges on methods useful to students and researchers for unfolding and decoding natural processes and applying

them to design. Reproducibility (as in extrapolation), autonomy, self-maintenance, and data synthesis — processes of knowledge construction — are then primary goals autopoietic-extended design supports as generatively prior to algorithmic simulation and fabrication.

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1.4 • Scaffold Building

Cognitive, perceptual, and sensory constructs, frequently accompanied by their synthetic and technological counterparts (data from objects/environments), are phenomenological/physical components of environmental systems. Together they bond data (natural, technological, and structural) as deployed and flowing in nature. Andy Clark, discussing extended cognition and cognition's relationships with the environment finds that:

It remains the substantive empirical bet of the extended systems theorist that larger hybrid wholes, comprising biological and non-biological elements will . . . prove to be the proper objects of sustained scientific study in their own right (Clark 2007b 168).

"Larger hybrid wholes" are represented in this thesis as autopoietic *unities* comprised of *student + technology + environment* (and other configurations) working in autopoietic-extended design domains (Stevison 2008). Hybridized components then facilitate cognition-to-matter and thought-to-fabrication understanding of data on its way to influence generative architecture. With those autopoietic unities — autopoietic-extended design helps organize data input for visualizing design filtered through complexity and emergence (Fenwick *et al.* 2011. Mason 2008a. b). Weber and Varela state that:

[A]utopoiesis is a singularity among self-organizing concepts . . . close to strictly empirical grounds, yet provid[ing] the decisive entry point into the origin of individuality and identity, . . . connecting . . . into the phenomenological realm (Weber & Varela 2002 116).

Autopoietic-extended design developing here as a method of learning and thinking, collaborates in a corrective to Cartesian mind/body and body/nature dualisms (Gibson 1986. Jonas 1965. 1966). It replaces dualisms with an environmentally symbiotic (Margulis 1999) approach to experimental architecture that is compatible with extended phenotypes (Dawkins 1982), as well as with Odling-Smee's (1996) views of "niche constructions." Autopoietic-extended design then assists factoring in biological, cognitive, and naturally engaged design pedagogy that is operable without Cartesian disregard of the environment's role in thinking.

As an operational foundation, the OS eases students into positions to conceptualize new ways of integrating machines and nature (Stevison 2008) through the examination of metabolic, morphological, and mechanical functions required by performative building systems (Armstrong 2012. Spiller 2009). Ultimately, the primal nature of shelters found in the animal kingdom — built constructions as extended phenotypes (Hansell 2005) — align tool making and architecture's ancient historic, ontological, and epistemological systems (Dawkins 1982. Herrmann 1984. Malafouris & Renfrew 2010. Meinesz 2008. Odling-Smee *et al.* 2013). Following that ancestry, the OS is cleared for aiding the evolution and conceptualization of buildings, metabolizing systems, and ALife by helping to channel data to students to use for decoding and shaping morphological and metabolic design potential.

Before turning to Sullivan and Turing, I smooth a way to conceptualize extended phenotype's use in AI, ALife, computational botany, morphogenesis, and architecture. In my OS construct, extended phenotypes illustrate the near-universal activity of building — niche, web, nest, smartphone, burrow, cocoon, gall, shell, and skyscraper. As constructions, extended phenotype's role between living and inanimate nature, may be seen by designers to illustrate genetics extending through metabolism to tool and environmental manipulations (Dawkins 1982. Langton 1988. Rieffel *et al.* 2013. Weber *et al.* 2013).

The connection between forms built in nature by organisms and their genes has recently been DNA sequenced (Weber *et al.* 2013). Equally relevant, the synthesis of building, matter, technology, and environment in specie-wide ontological struggles (Dawkins 1982. Hansell 2005. Turner 2000) — may be parallel in human constructions bonding nature to architecture; even when mediated by synthetically produced materials. I see that bond as a stimulus for developing new methods for teaching generative design in the context of AI and living technology (Bedau *et al.* 2010. Langton 1996. Venter 2013). With Dawkins's (1982) well-known hypothesis of extended phenotype in mind (Hansell 2005. Turner 2000), I then read the clarity of Christopher Langton's "Artificial Life," for its extension of *phenotype* outside genetics and biology in his context of ALife:

The most salient characterization of living systems, from the behavior generation point of view, is the *genotype/phenotype* distinction. The distinction is essentially one between a specification of machinery — the genotype — and the behavior of that machinery — the phenotype.

The *genotype* is the complete set of genetic instructions encoded in the linear sequence of nucleotide bases that makes up an organism's DNA. The *phenotype* is the physical organism itself — the structures that emerge in space and time as the results of

the interpretation of the genotype in the context of a particular environment. The process by which the phenotype develops through time under the direction of the genotype is called *morphogenesis* (Langton 1988 22 original emphasis).

Langton's view of morphogenesis now adds after-the-fact insight to Sullivan's morphology (1999) and Turing's morphogenetic papers (1952. 1953) via genotype/phenotype relationships bolstering current notions of generative form as derived from nature with computational significance — what Lynn (1999 11) called “gradient forces” and “generative fields.” In Langton's context, Dawkins's (1982) extended phenotypes reinforce autopoietic-extended design's inclusion of off-body forms and systems expressing material, metabolic, and sometimes-intelligent constructions akin to a spider's web or a bird's nest (Hansell 2005. Turner 2000).

Dawkins wrote and programmed ALife computer experiments. He tested theories in a virtual world he called “Biomorphs” (Dawkins 1988 201) that computationally generated extended phenotypes as stick drawings related in code to John Conway's *Game of Life* (Emmeche 1994. Gardner 1970). And, as already discussed (Section 1.3), Varela, Maturana, and Uribe's computational autopoiesis attempted to algorithmically model digital life (Varela *et al.* 1974. McMullin & Varela 1997. Uribe 1981. Varela 1979). All three — Biomorphs, *Game of Life*, and autopoietic cellular automata — have digital-evolutionary programming related to Dawkins's *Central Theorem of the Extended Phenotypes*:

An animal's behavior tends to maximize the survival of the genes [or cellular matrix for algorithms] “for” that behavior, whether or not those genes happen to be in the body of the particular animal performing it (Dawkins 1982 233).

For a wider view of evolutionary selection that balances Dawkins's focus on genetic inheritance, and to associate phenotype building and environmental modifications with evolutionary selection, I sought contemporary research in the area of “Niche Construction Theory” (Odling-Smee 1994. Odling-Smee *et al.* 2013). This theory addresses aspects of cognition, environment, phenotypes, species habitat construction, and biology with an evolutionary scope that favors autopoietic-extended design's chances of survival.

Buttressing this dissertation's scaffold, Odling-Smee's (1994) niche construction theory describes extended phenotypelike feedback and adaptation in the natural world, particularly in relation to built works, objects, and environments as they affect the builder and, for this thesis, are compatible with Clark's version of extended cognition. Here “Niche Construction, Genetic

Evolution and Cultural Change" speaks for the evolutionary importance of built structures:

Populations of organisms, through their metabolisms, their behaviors and their choices, define and partly create their own niches. They may also partly destroy them (Waddington, 1959; Lewontin, 1983). I call these phenomena either positive or negative niche construction.

The significance of niche construction is that it introduces feedback from the adaptations of organisms to sources of natural selection in their environments. Adaptation is traditionally viewed as a process by which natural selection moulds organisms to fit pre-established environmental templates (Burian, 1992). It is widely recognized that these templates are dynamic, because independent forces often change the worlds to which organisms have to adapt (Van Valen, 1973). However, the changes that organisms cause in their own worlds are seldom considered to be evolutionarily important. In reality, many selection pressures only exist because of the prior niche constructing activities of many generations of organisms (Lewontin, 1983). Hence, the adaptive fit between organisms and their environments results from selection acting to mould organisms to environmental templates, which are at least partly self-constructed (Odling-Smee 1996).

Ultimately, the evolution of tools and architecture falls into the category of species-built objects and habitats with concurrent cultural selection and adaptation pressures partially processed as extended phenotypes (Dawkins 1982. Hansell 2005. Turner 2000). And, given the diversity of species and their constructions:

[T]hese extended phenotypes have similarities: they seem to be constructed through largely unlearned motor patterns; they are often consistent within a species (or population); and, when architectures differ, these differences reflect important fitness-related functions in the wild (Weber *et al.* 2013).

Autopoietic-extended design taps into the view of architecture as a tool/machine (Chapter 5. 5.2) enabling users technological abilities for communicating and cultivating design input/output manifested as extended phenotypes. I am not attempting to explain for example, how neurological cognition, extended phenotype expression, or visual perception functions, nor am I asking why they function (Dawkins 1982. Weber *et al.* 2013). I am concerned, rather with generative design ideas connected via technological tools to thinking and theory as they

contribute to form-finding, performance, and m-learning (Clark 2008a). Through this descent, and toward design output, I steer autopoietic-extended design toward class situations for testing efficacy of idea generation, project development, and fabrication (Dollens 2012. 2014):

If it is shown how things are made up of their elements, it is also shown, on principle, how they can be made up out of such elements. Making, as distinct from generating, is essentially putting together pre-existing materials or rearranging pre-existing parts (Jonas 1966 202).

In this sense, autopoietic extrapolation may be activated by students during in-field observation and while doing research to use digital data input/output as they occur, first toward generating ideas and then to the making of drawings, structures, materials, and models (Jonas 1966. Weinstock 2006b). On behalf of the idea that architecture is part of nature, and from the perspective of rigorous optical and technological observation of nature, I seek a pedagogical OS supporting the use of biological and synthetic data capable of instituting a new genealogy of generative architecture and pedagogy metabolically emergent in: Can buildings think?

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1.5 • OS Works

The autopoietic-extended design OS functions to organizationally and ontologically orient students toward research in relation to biological and phenomenological data sources. As Randall Beer points out:

Many of the key behavioral and cognitive implications of Maturana and Varela's framework follow from autopoiesis; they do not require a complete account of autopoiesis for their exploration and application (Beer 2004 319).

Beer's quotation encourages me to hybridize autopoiesis outside "a complete account" of its original form. Thereafter autopoietic-extended design, not being a pure enactment of Maturana and Varela's (1980) theory, accepts adaptation enabling new OS design output. For my thesis and the OS itself, recursive integration of theory is necessary to provision data flow (Gibson 1986), selection, and adaptation (Di Paolo 2005. Weber & Varela 2002) — yet most students will encounter only a non-theoretical set of procedures and examples for a research framework. Instead of focusing on theory, student interactions focus on nature for design ideas or environmental problem solving, while the OS theory operates behind the scene.

Analytical sourcing of nature aligns with what Michael Weinstock (2006a 27) calls "engineering principles of biological systems . . . abstracted and applied to the design of artifacts and buildings, a process known as biomimetics." In a digitally oriented biomimetic program, generative design is collaborative across systems and networks connecting the designer with nature via computer, software, and programming. Weinstock, in a parallel text, elaborates: "Biomimetics is essentially interdisciplinary, a series of collaborations and exchanges between mathematicians, physicists, engineers, botanists, doctors, and zoologists" (Weinstock 2006b 35-36).

The autopoietic-extended design OS is then a generative guidance system (Chapters 1. 1.3 & 5. 5.2) aiding students' interpretation of data. Nature is an input/output source for subsequent design expression via digital-biomimetic procedures potentially aligning with metabolic architectural performance (Ball 2001. Greenberg & Jeronimidis 2013. Weinstock 2006b). Student goals and project intentions then merge — nurtured — through design research with technologically acquired data that reinforces algorithmic simulations, animations, renderings, CAD, and machine fabrication as first instantiated in thinking and then instrumental as biodigital research where:

The behavior of all natural systems is complex and adaptive, and plants in particular manage their structural behavior in a way that provides new models for engineered structures (Weinstock 2006a 27).

Emergent, complex, and adaptive autopoietic-extended design supports the generation of ideas in this context and in sync with living organisms, inert matter, and physical forces because it positions technology as collaborative — tools cognitively extended as part of nature (Clark 2003. Johnson 2001. Jonas 1966. Odling-Smee *et al.* 2013. Thompson 2007 60). By cultivating autopoietic-extended design in a glasshouse environment of university teaching, in-field research, and student selection, metabolic generative architecture emerges as a theoretical cultivar assisting student observation and visualization.

I cull archival sources for supplemental and adaptive views of both autopoiesis and extended cognition so that autopoietic-extended design may take root and branch in subsequent chapters. Below I look to "Autopoiesis, Adaptivity, Teleology, Agency," by Ezequiel Di Paolo, as he quotes Maturana and Varela, and Weber and Varela:

Central to the theory of autopoiesis is the axiom of structural determinism: changes of state in a system always operate in the present as a result of [the system's] current structure and are not determined by external agents or contextual conditions. With this

axiom in mind, an autopoietic system is defined as:

"A network of processes of production (synthesis and destruction) of components such that these components:

1. continuously regenerate and realize the network that produces them, and
2. constitute the system as a distinguishable unity in the domain in which they exist" (Weber & Varela 2002 115).

Formally interpreted, this definition . . . has often been supplemented. . . . For instance, autopoietic systems conserve their organization by "maintaining constant certain relations between components otherwise in continuous flow or change" (Maturana & Varela 1980 81), as opposed to systems that are static and simply endure (Di Paolo 2005 434).

Having outlined autopoiesis as Maturana and Varela (1980) conceive it, Di Paolo (2005) sees that the original theory requires "supplemented" adaptation. Di Paolo's adaptations on occasion dovetail with other scholars' opinions as we saw earlier with Beer (2004 319) and below with Evan Thompson:

Autopoietic systems form a subset of *self-organizing* systems . . . interact[ing] with each other in non-linear ways to produce the emergence and maintenance of [their] structured global order. . . . [where] constituent processes "(i) *recursively depend on each other for their generation and their realization as a network*, (ii) *constitute the system as a unity in whatever domain they exist*, and (iii) *determine a domain of possible interactions with the environment*" (Thompson 2007 44 citing Varela 1979 55 emphasis added).

Following from the above, *emergence* considered in these pages finds further expression in Thompson's words:

In complex systems theory, an emergent process is one that results from collective self-organization. An emergent process belongs to an ensemble or network of elements, arises spontaneously or self-organizes from the locally defined and globally constrained or controlled interactions of those elements, and does not belong to any single element (Thompson 2007 60).

And, thereafter, Hensel provides a view of self-organization:

Self-organization is a process in which the internal organization of a system adapts to the environment to promote a specific function without being guided or managed from the outside (Hensel 2006 13).

Autopoietic self-organization through molecular and/or phenomenological attraction, affinities, or accident promotes examining liminal processes in matter, force, life, and intelligent environments (Di Paolo 2005. Maturana & Varela 1980). To become environmentally active, autopoiesis needs theoretical reach outside its own operational closure. I address this requisite to gain traction for autopoietic-extended design outlined below in three comments, first from Richard Menary, then John Sutton, and lastly from Andy Clark:

The extended mind is not simply an embodied-embedded thesis that treats external props and tools as causally relevant features of the environment. It is a thesis that takes the bodily manipulation of external vehicles as constitutive of cognitive processes (Menary 2010 21).

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Many of our cognitive states and processes are hybrids, unevenly distributed across biological and nonbiological realms. . . . In certain circumstances, things — artifacts, media, or technologies — can have a cognitive life, with histories often as idiosyncratic as those of the embodied brains with which they couple. . . . The realm of the mental can spread across the physical, social, and cultural environments as well as bodies and brains (Sutton 2010 189).

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What makes such interfaces [agent + object/environment] appropriate as mechanism for human enhancement is, it seems, precisely their potential role in creating whole new agent-world circuits. But insofar as they succeed at this task, the new agent-tool interface itself fades from view, and the proper picture is one of an extended or enhanced agent confronting the (wider) world (Clark 2007a 4).

These descriptions of extended cognition allow orienting it with autopoiesis since both display powerful self-organization commonalities where hybridization simultaneously strengthens the emerging pedagogical and research scaffold. To begin with, an autopoietic unity provides the opportunity for further defining an *operationally closed* working group that:

... reflects the necessity of understanding cognitive systems not on the basis of their input and output relationships but by their *operational closure*. A system that has operational closure is one in which the results of its processes are those processes themselves (Varela *et al.* 1992 emphasis original).

I therefore constitute an autopoietic unity from three environmental components native to architectural design: *student + technology + environment* that outputs more design. When student engaged, this unity addresses specific autopoietic domains involving learning, knowledge, observation, and communication and remains open to extended cognition. Learning is considered a domain of action since observation and contemplation are partially physical, while knowledge is a domain of constructed experiences, often self-organizing in both physical and phenomenological domains — therein, learning, design, and knowledge are inseparable, but nevertheless, capable of being nurtured, constructed, and evolved (Lewontin 1983. Luhmann 1990. 1990a. 2000).

For autopoietic-extended design, nurtured or cultivated learning initiates communication of data for insight (knowledge construction) from physically occupied research sites for experience (Gibson 1986) met and mediated by the OS and its associated technologies. In a phenomenological sense, *student + technology + environment* unite as temporary symbionts (Margulis 1999). To that student unity, technology, partially implemented by smartphones and apps, routes AI-sourced data to support translation of research, production, and communication.

The OS thus provides a protocol from which to conduct and organize in-field research — a launching platform for e- and m-learning classes seeking to investigate metabolic building performance (Bedau *et al.* 2010. IBM 2011. Floreano & Mattiussi 2008. Jah 2010. Spiller & Armstrong 2011. Venter 2012). Toward this objective I read, Bedau *et al.* (2010. 2013) and Venter (2013) discussing useful alternative categories for life and for experiments with living organisms, captured in the "three main synthetic methodologies in artificial life: soft, hard, and wet" (Bedau *et al.* 2010 94).

Related to soft, hard, and wet and in the context of previously mentioned projects by Adamatzky's (2013), IBM's (2011), and Stanford/Venter (Markoff 2012) scientists have identified, for example, "floral electrical-fields" used by bees and flowers (wet) to communicate (Clarke *et al.* 2013). This discovery, announced in *Science Magazine*, suggests localized interspecies messaging with chemical and electrical signaling that relates to parallel research taking place in plant neurobiology (Brenner *et al.* 2014. Gagliano *et al.* 2014. Mancuso 2010. Mazzolai 2010). While years away from practical extrapolation, animal/plant signal detection

illustrates the role experimental design research, in conjunction with technology and biological science, could play in metabolic architectural visualization.

In this mode, related to plant signaling (Clarke *et al.* 2013) and new modes of communication established by Mousavi *et al.* (2013), are pathways for innovative systems and materials designed to recognize alternative cognitive communication in environmental monitoring and sensing (Armstrong 2010). This vein of design research touches biorobotics and edges toward defining bio-responsive (machinic) building performance dependent on metabolic monitoring, sensing, or subsystem actuation. In such a register, Weinstock and Stathopoulos distinguish models from simulation:

A model is an abstraction of a process, and can be refined as understanding of a process develop[ing], so that complex problems can be accurately modeled. Simulations are essential for designing complex material systems, and for analyzing their behavior over extended periods of time (Weinstock & Stathopoulos 2006 59).

The bee-to-flower, flower-to-bee signaling (Clarke *et al.* 2013) could be narrated as cognitive organism (bee) communicating with animate (but non-conscious) plant, or it could be modeled and simulated with a building in the role of the flower and programmed agents, *animats* or biorobots, in the role of the bees (Webb 1996. 2001. 2009). In the latter analogy, a research building in the role of agent could illustrate a close-range communications network with biorobotic actuators establishing hybrid metabolic intelligence performing architectural, environmental, and communication functions (Clarke *et al.* 2013. Di Paolo 2010. Gagliano *et al.* 2014).

These speculations, resulting from observation of nature, flower-to-bee for example, monitor science and technology as data, mechanisms, or insight sources available for architectural conceptualization and appropriation (Bedau *et al.* 2010. Clarke *et al.* 2013. Mousavi *et al.* 2013. Weber *et al.* 2013). They represent draft narratives for learning new routines involving metabolic systems in nature (urban or wild) using an OS geared to work both onsite/online and in studios or classrooms.

Crossover research into science or technology for design may be manifested through texts, drawings, websites, and video to alert designers to physical models or algorithmic simulations taking on tasks that in the past were outside of design channels — all delivered to students through the OS. My own design practice addresses autopoiesis and extended cognition for ways-of-observing — conceptualizing metabolic and morphological buildings — and then ways-of-designing plant systems for architectural structures and components (Figs 6-10a, pp76-

89). In these simulations I hybridize morphological attributes (trees, branches, buds, leaves, and their growth and phototropic/gravitropic extension) to prototype digital plants as structural armatures. Those botanic simulations are then exported as architectural components for drawings, STL file prep, and rendering in Rhino and 3D Max. The resulting structures have their point of origin embedded in plant morphology expressed through L-systems (Chapter 5. 5.4) powering, for example, the software Xfrog (Deussen & Lintermann 2010 89).

This research has resulted in my design derivations owing to Louis Sullivan's (1990) *A System of Architectural Ornament* (Chapter 4) and Turing's (1952. 1953) Morphogenetic simulations (Chapter 5) where formal geometric trellises (matrices) are overgrown with rule-based plant growth — what, for my simulations I call e-trees (Figs 6-10a, pp76-89) — algorithmically hybridized in digital systems and fabricated as STL models.

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1.6 • eTrees & Autopoietic-Extended Design Practice

Figures 6-10a (pp 76-89), illustrate experimental designs for investigating adaptive botanic intelligence and morphology in order to yield ideas for generating the metabolic architectures that are at the heart of my own autopoietic-extended design practice. I developed procedures for biologically simulating plant growth in order to model armatures so they might serve as primer-morphologies for intelligent, bioresponsive building structures. Within this frame, I consider these models as physical manifestations of the autopoietic-extended design program that generated them and that, thereafter, they help refine — causal and recursive determinates in stepped progressions toward theoretical OS articulation and materialization. These simulations carry embedded and extended data as cognitive-state objects functioning via autopoiesis (Maturana & Varela 1980) and Clark's (2008a) hypothesis of extended cognition (Chapters 1. 7).

As presented, the Xfrog/L-system simulations (Figs 7, 7d, 10) and 3D stereolithographic (STL) models (Figs 7a, 7c) reconfigure plant growth, balance (component distribution), and scale by manipulating botanic characteristics first observed then visualized and prototyped in order to harness phyllotaxy, parastichy, gravitropism, and phototropism. Moreover, the models and their digital files embed genetic algorithms (dormant or active) that influence attributes of branch section, length, spiraling, tapering, budding, and leafing in subsequent phases of component growth. The models' branching, whirling, and exaggerated overgrowth enables alternative anatomical performance delivered in self-bracing or (triangulation-like) mutual reinforcement controlled by the intersecting, perforated, or bonded assembly of components. Metabolically implemented, shape-shifting, and network determining performance then mutually reinforces communicative and skeletal adaptability — simulated in models — for design tactics capable of agent-directed building-to-environment response.

While choice of the models from the serial Xfrog images (Figs 7, 7d) may appear aesthetically arbitrary, no single aesthetic preference determines their selection. Satisfying requirements (e.g., branch intersections and joinery) for overall eTree movement leaves few generative configurations capable of flex in single or combined x-, y-, or z-orientation(s). So, only in the initial programming or far into the generative process after an eTree demonstrates twist, folding, or collapsibility can aesthetic decisions come into play.

The eTrees' evolvable configurations (all relating differential, proportional growth) populate a new typology comprised of simulated trusslike structures, matrices, substrates, or armatures. At present, the eTrees exhibit the limited range of the proto-animate abilities of flexing, stretching, and twisting already mentioned. Yet these movements demonstrate necessary structural attributes and modes of expression from which properties of living systems (e.g., bone shear, blood circulation, muscle pathways) may be contemplated. Therefore, the structural systems of eTrees are critical for metabolic buildings in the category of digital-botanic architecture that I investigate. At the next stage, the skeletal trusses are intended to test aerodynamic, seismic, and tropic input/output responses assessed in simulations or prototype skin, muscle, and/or responsive monitoring in living organisms.

The properties just listed are not foreign to plants or animals but animate/metabolic skills are new to buildings and are only now emerging in theoretical architecture (Armstrong 2012. Cronin 2011). As the physical expressions of design ideas, the STL eTrees drive learning and form-finding to cultivate architectural performance intended to meet environmental challenges. To this end students seek attributes found in animate nature in order to envision functionings and to facilitate the transfer of properties from sense-making plants and bacteria to architecture. (Baluška & Mancuso 2009. Brenner 2006. Mancuso 2010. Pollan 2013).

Moving design research toward living, self-maintaining, sense-making organisms is thus one goal of autopoietic-extended design. To continue that move vis-à-vis eTrees, I contemplate (postdoctoral) refabrication of the current model files with a living, 3D printable bioresin (Atala 2011. Fountain 2013). After that, I imagine hybridizing secondary cellular-intelligent (leaf/skin/membrane) systems with (or sprouting from) eTree matrices. For, the second option, I visualized (Figs 7g, 9, 10a) as hypothetical membrane-clad intelligent structures to design urban-scale building panels. These rendered models and their 3D files embody working concepts at preliminary stages of process/structure integration, where eTrees generate building envelopes, superstructures, and schematics for algorithmically growing leaflike or podlike facade components (Figs 7d, 7f, 10). Enlisted for architectural design-by-research practices, such models prompt discussion that may lead to evolving design and learning ideas, predicated as metabolic and based on plant or bacterial sense-making (Brenner 2006. Pollan 2013).

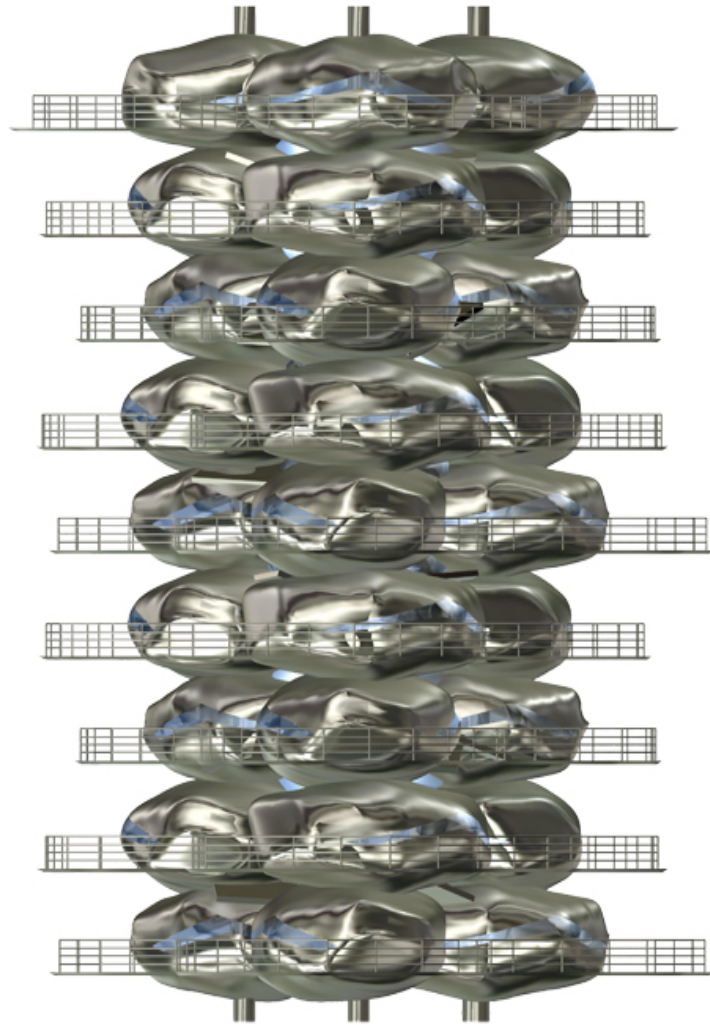
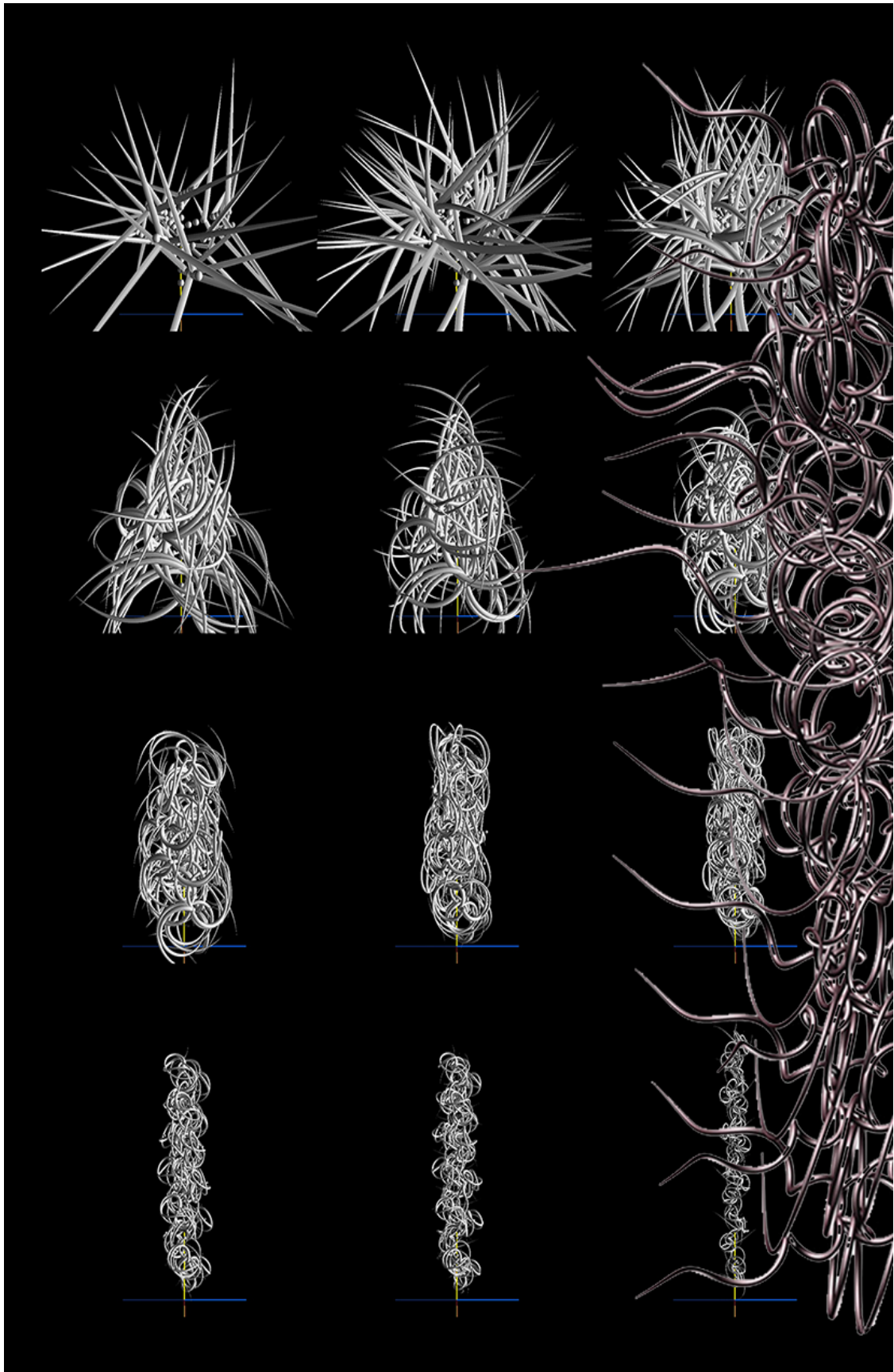


Fig 6. Glasgow Tower. Dennis Dollens. Tower morphology generated from the stalks and seedpods of *Penstemon palmeri* (right) as an experiment in botanic-form generation reflected to architectural and autopoietic typologies. Xfrog/Rhino/3DS.



Fig 6a. Glasgow Tower. Foreground. *Penstemon palmeri* seedpod clusters along a vertical stalk studied as a model for morphological pattern, airflow, and light distribution data using Xfrog/Rhino/3DS Max. Background, the 3DS Max rendering of the residential tower collaged onto an image of the Glasgow site. Photo-collage: Dennis Dollens.



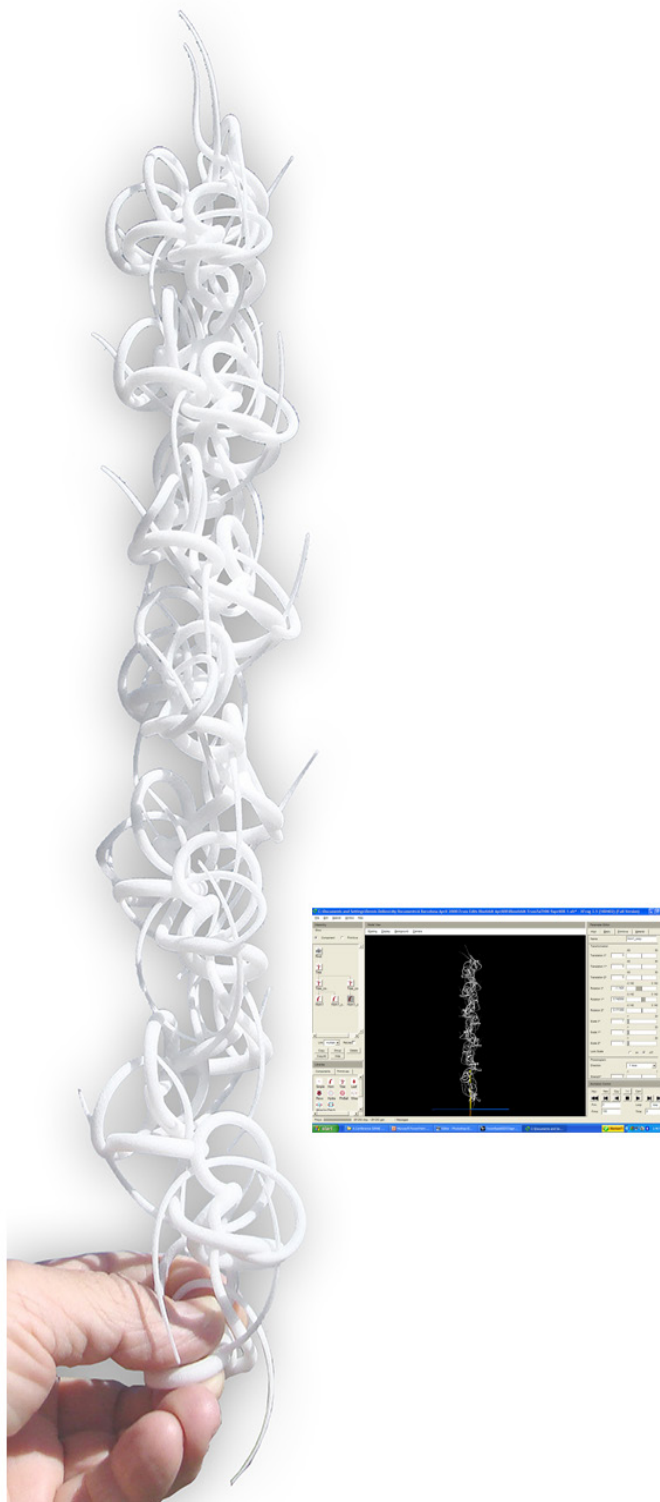


Fig 7, Left. Dennis Dollens. e-Tree Generative Sequence illustrating digital growth from initial programming to selected 3D file for export.
 Fig 7a, Above. e-Tree. Dennis Dollens. Digitally hybridized tree simulation generated in Xfrog's L-systems (screenshot insert), exported to Rhino and built as an STL model to test and illustrate computationally evolved tree branches intersecting each other to create a trusslike structure capable of degrees of environmentally-responsive bending or twist under stress. Xfrog/Rhino/3DS Max.

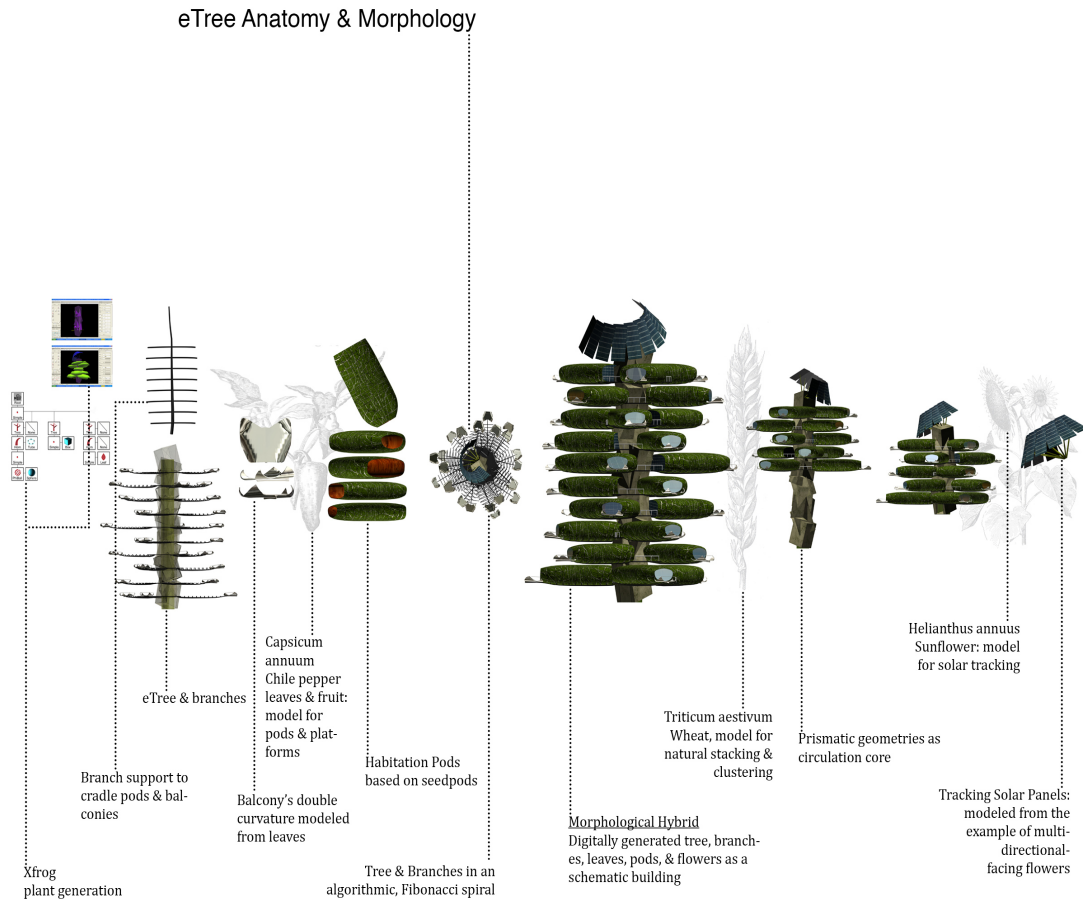


Fig 7b. eTree Anatomy & Morphology. This series of experiments with simulated digital trees, hybridized into architectural elements, illustrates botanic forms and their morphological and simulated attributes applied to design systems and structures. Using this generative process demonstrates how the transference of some biological properties, held in algorithmic notation, such as phyllotaxy, allometry, and phototropism may be inherited by architectural and design elements derived from plant simulations and their corresponding biological maths. Simulations: Dennis Dollens.

eTree Branch & Tendril Morphology

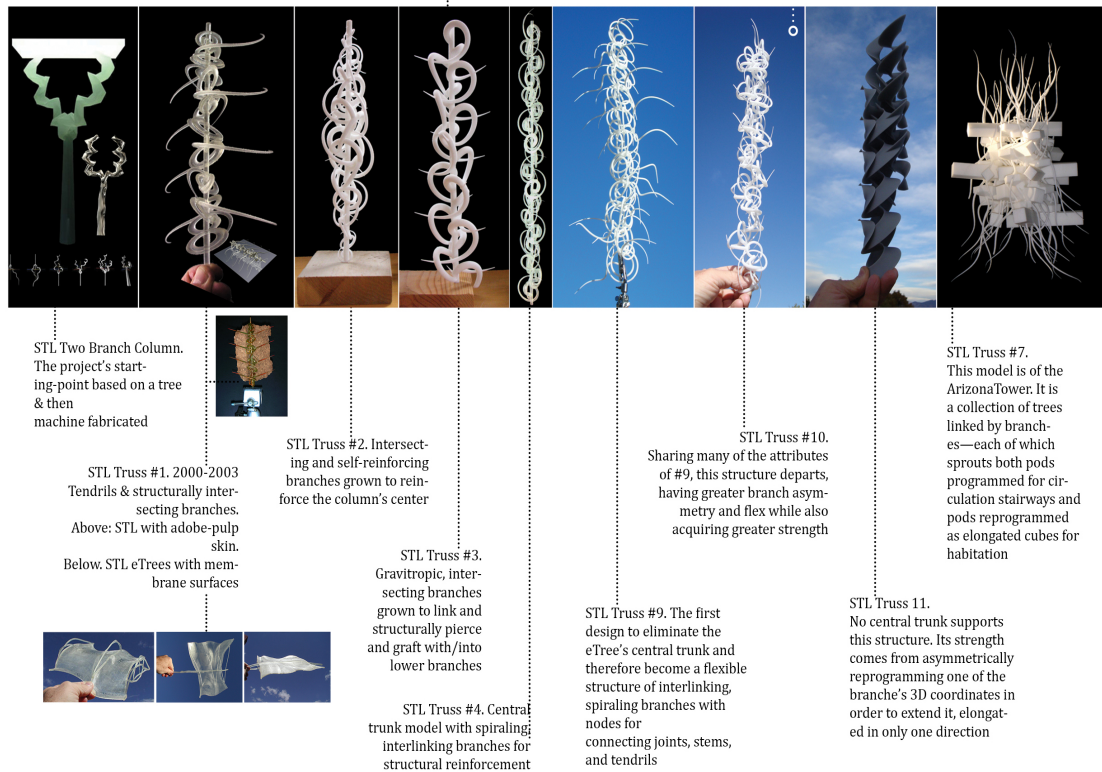
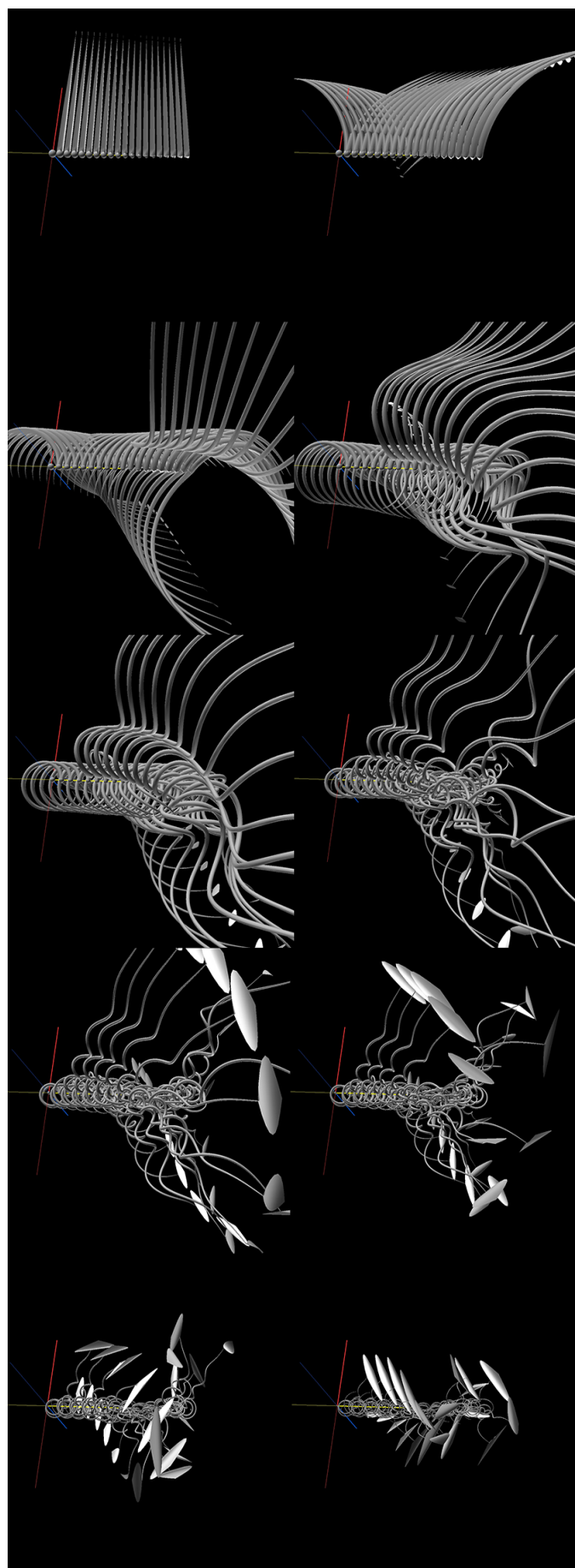


Fig 7c. eTree branch and tendril development evolving as multi-directional, flexing structural trusses that phase out central tree trunks. Simultaneously, the branches sprout secondary growths based on flowers, leaves, tendrils, and pods that are eventually reprogrammed as living or mechanical spaces in prototype buildings. Models & graphics: Dennis Dollens.



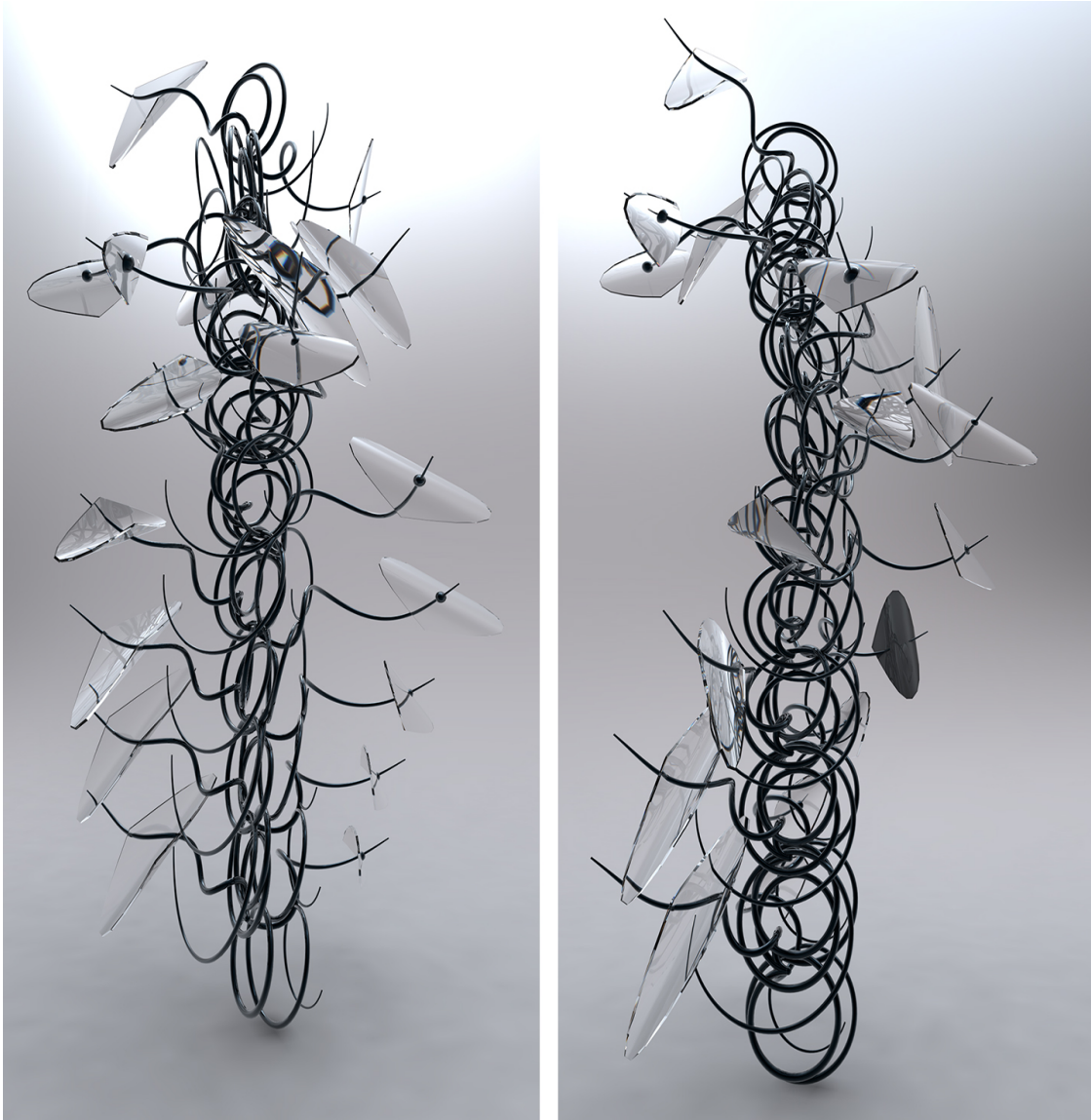


Fig 7d, Left. e-Tree Generative Sequence illustrating digital growth for leaflike forms/panels investigating plant-derived branch spiraling and double-curvature surfaces. Considerations for selecting a model's appropriate stopping point are established by structural intersections determined to balance action potential (flexibility for example) and trusslike strength.

Fig 7e, Above. e-Tree with leaves rendered as glass panels. Digitally hybridized tree simulation generated in Xfrog's L-systems, exported to Rhino, and rendered in 3DS Max to test experimental recursive surfaces following leaflike morphologies. Dennis Dollens.

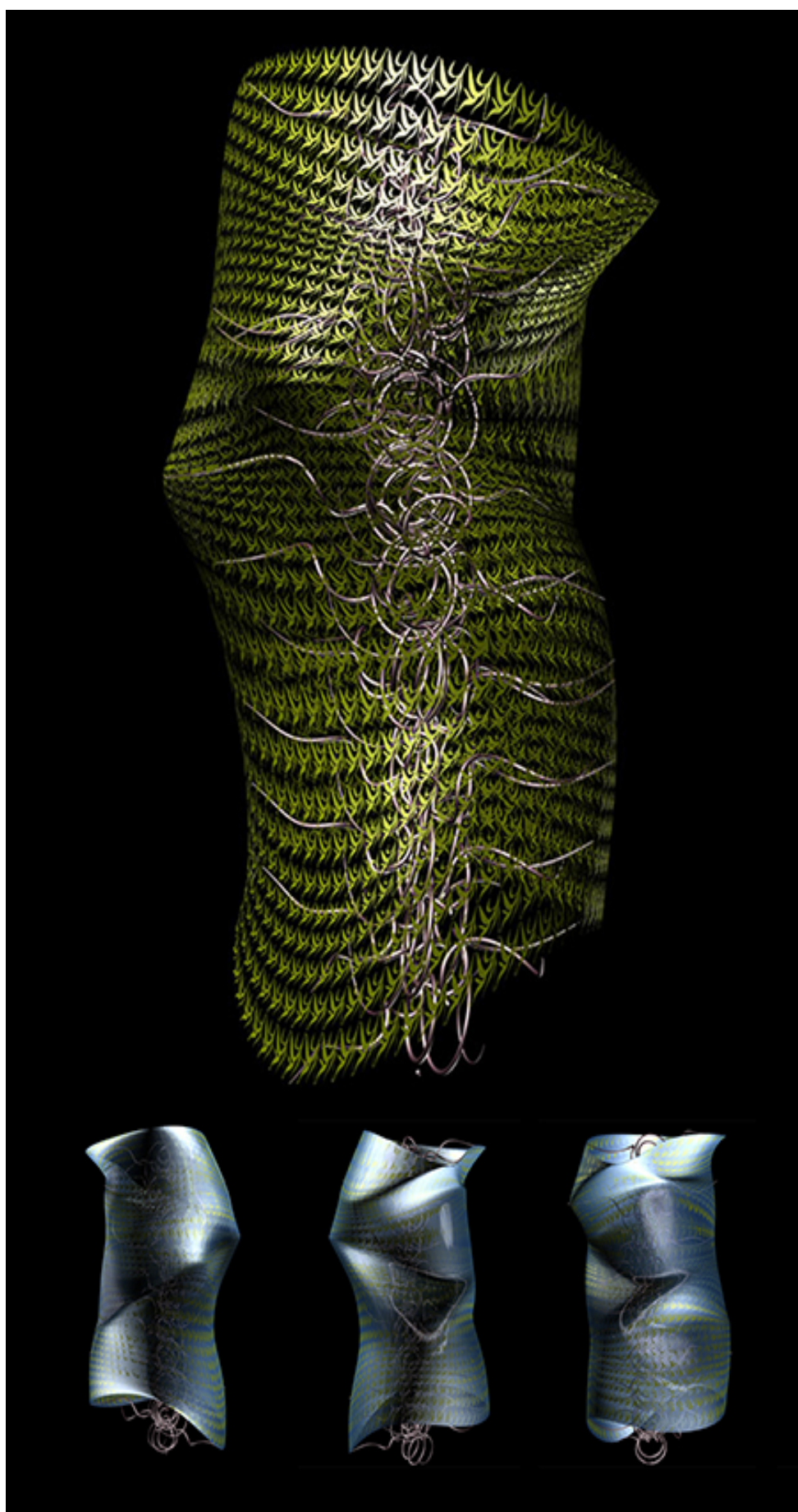
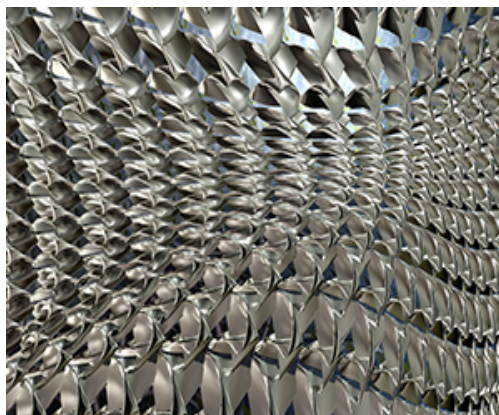




Fig 7f, Left. LA (Los Angeles) Tower. Parametrically generated leaf formation recursively used to fold an interlocking building skin comprised of differing-sized individual modules. The eTree branch tips define the building envelope and is later transformed into a service core (tree trunk) and floor joists (branches).

Fig 7g, Above. LA Tower. Leaf silhouette parametrically used to configure 2000+ differently scaled ventilation/breathing/sensing panels that also function to control natural light reaching the building's glass membrane. Xfrog/Rhino/ParaCloud/3DS Max. Dennis Dollens.

Fig 7h, Below. LA Tower skin detail.



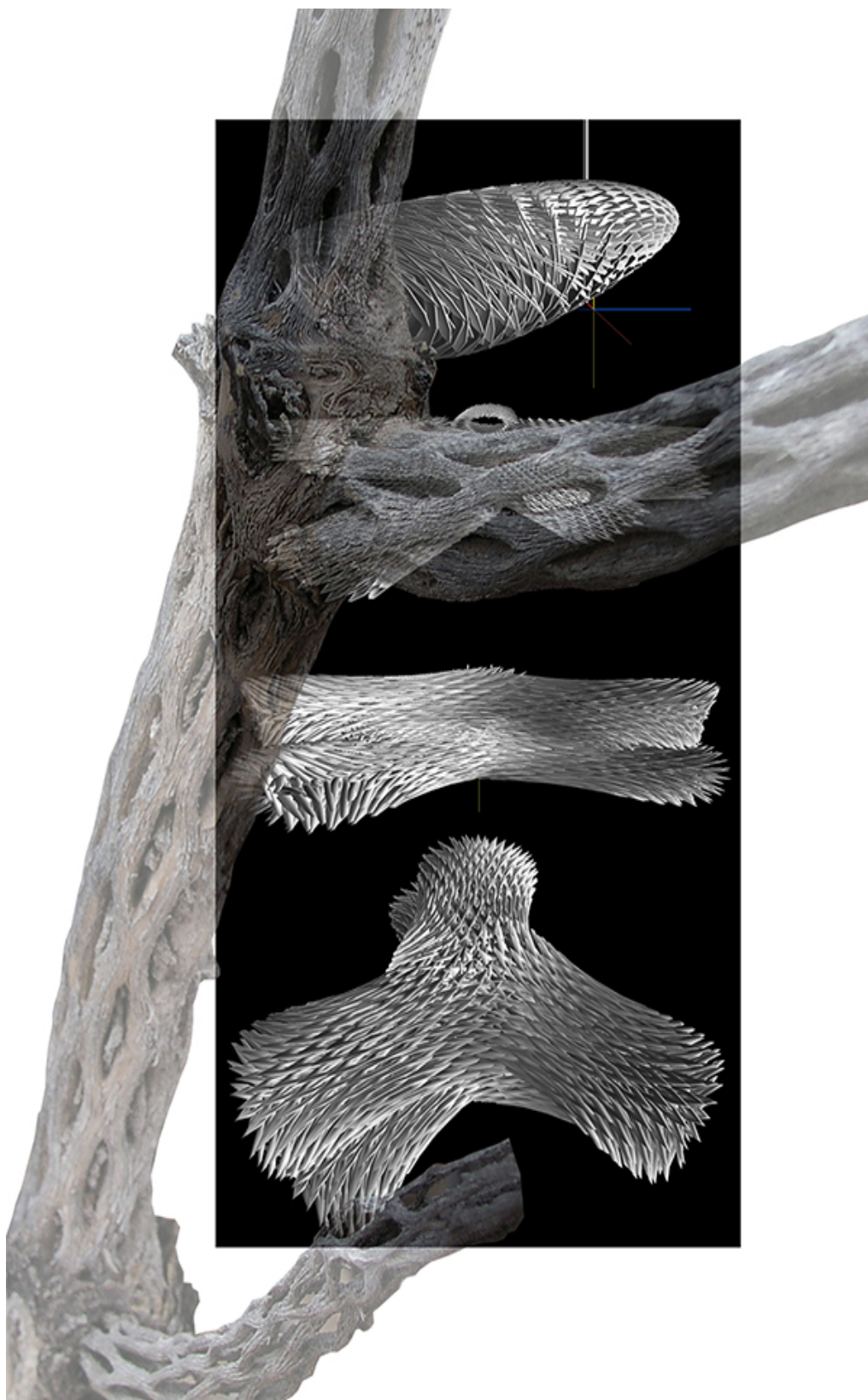


Fig 8. Exoskeletal Wood Growth. Cane Cholla (*Opuntia imbricata*) inspired Xfrog simulated weavelike experiments illustrating biomimetic observations-to-generative form to illustrate student exercises. Xfrog/Rhino/3DS Max. Dennis Dollens.

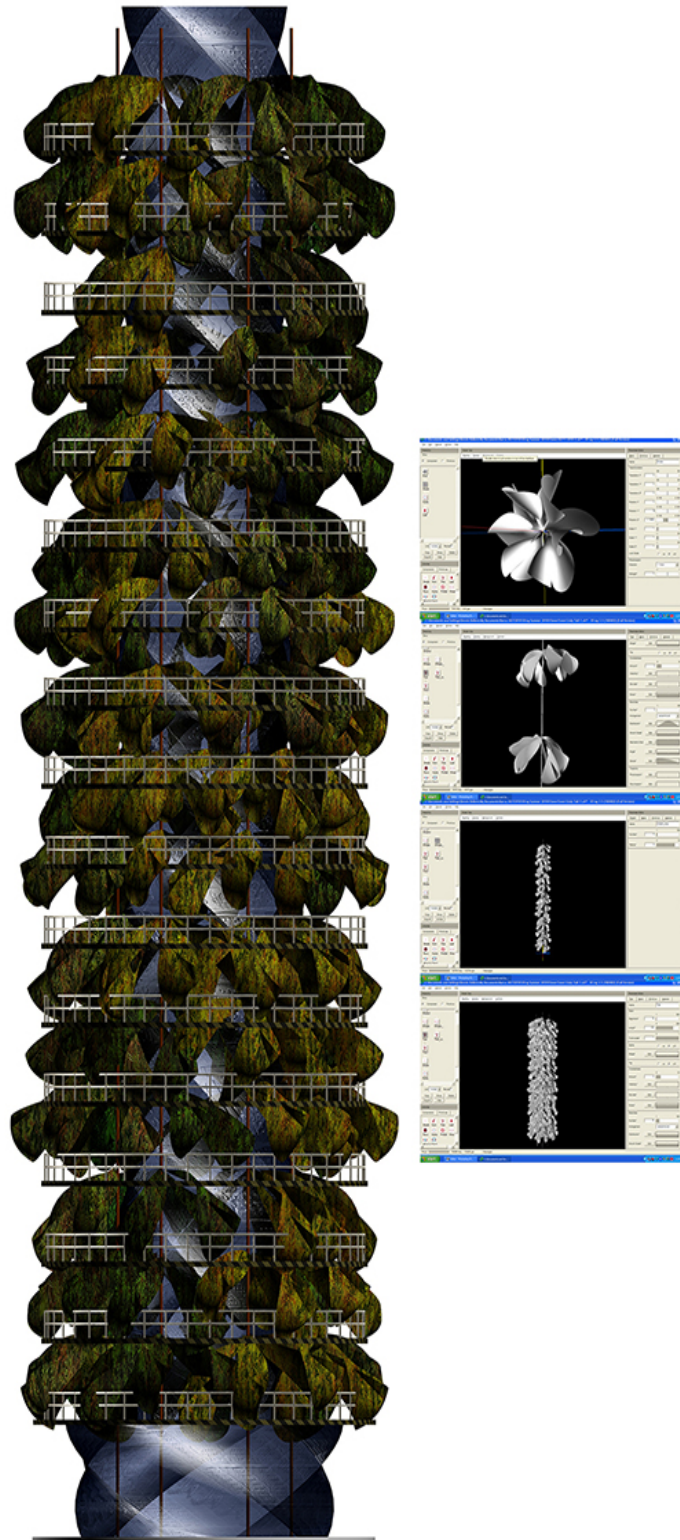


Fig 9. Pagoda Tower. Experimental growth from Xfrog (L-systems) for digital framing supporting contingent forms for biorobotic controllers moving and activating leaflike heat/light/sensor screens. Leaf-forms hold materialization potential for metabolic functions for bioremedial, environmental participation. Right: four Xfrog screenshots illustrating schematic leaf growths and distribution (phyllotaxis and parastichy) along a tubular, controlling stem. Xfrog/Rhino/3DS Max. Dennis Dollens.

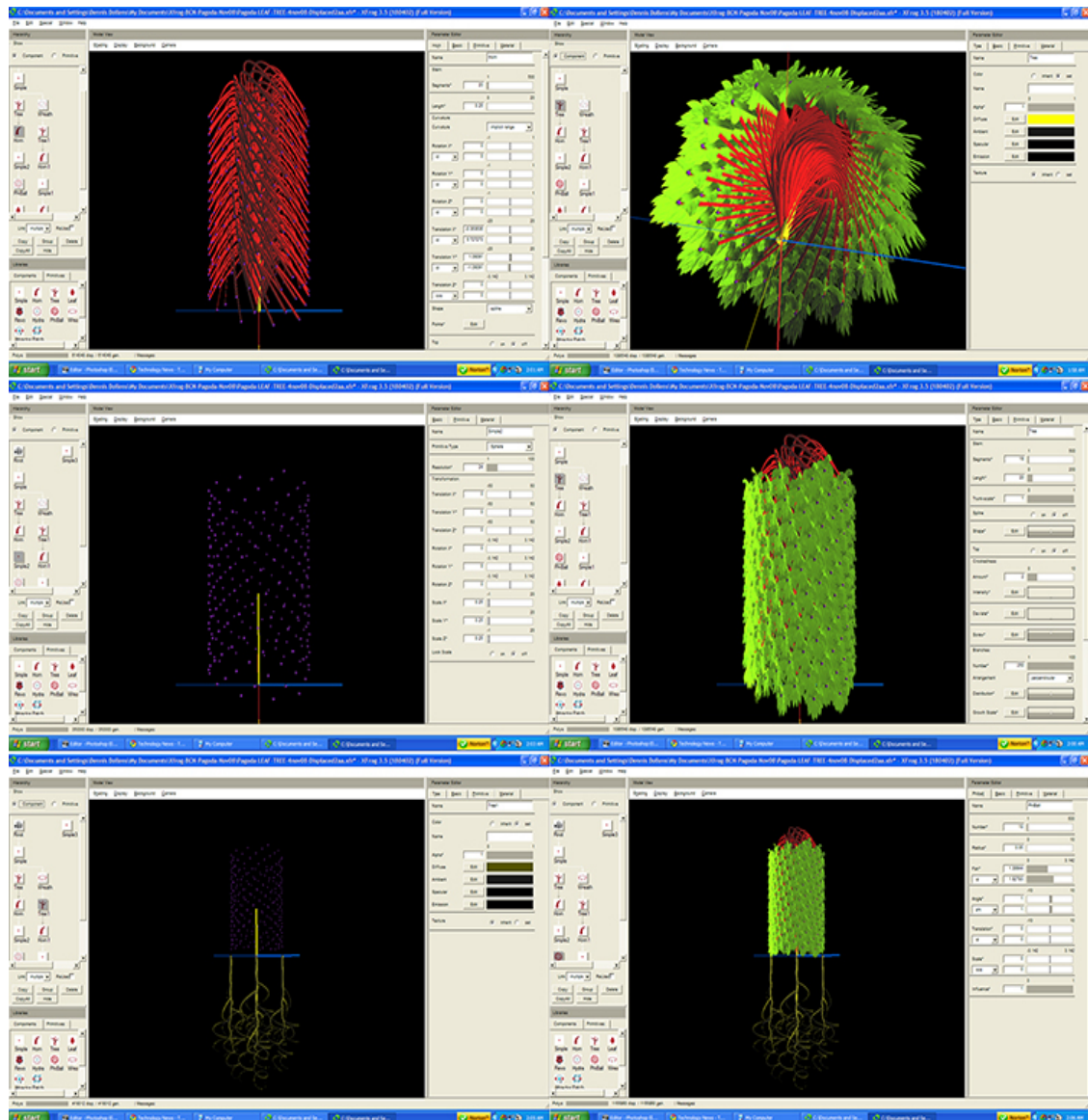


Fig 10. Six Xfrog Screen Shots. BioTower generative sequence involving (top-to-bottom, left-to-right) eTree branches; activator pods; roots; branches + leaves; branches + pods + leaves; tower with eTree + branches + pods + roots. (See: Fig 10a). Dennis Dollens.

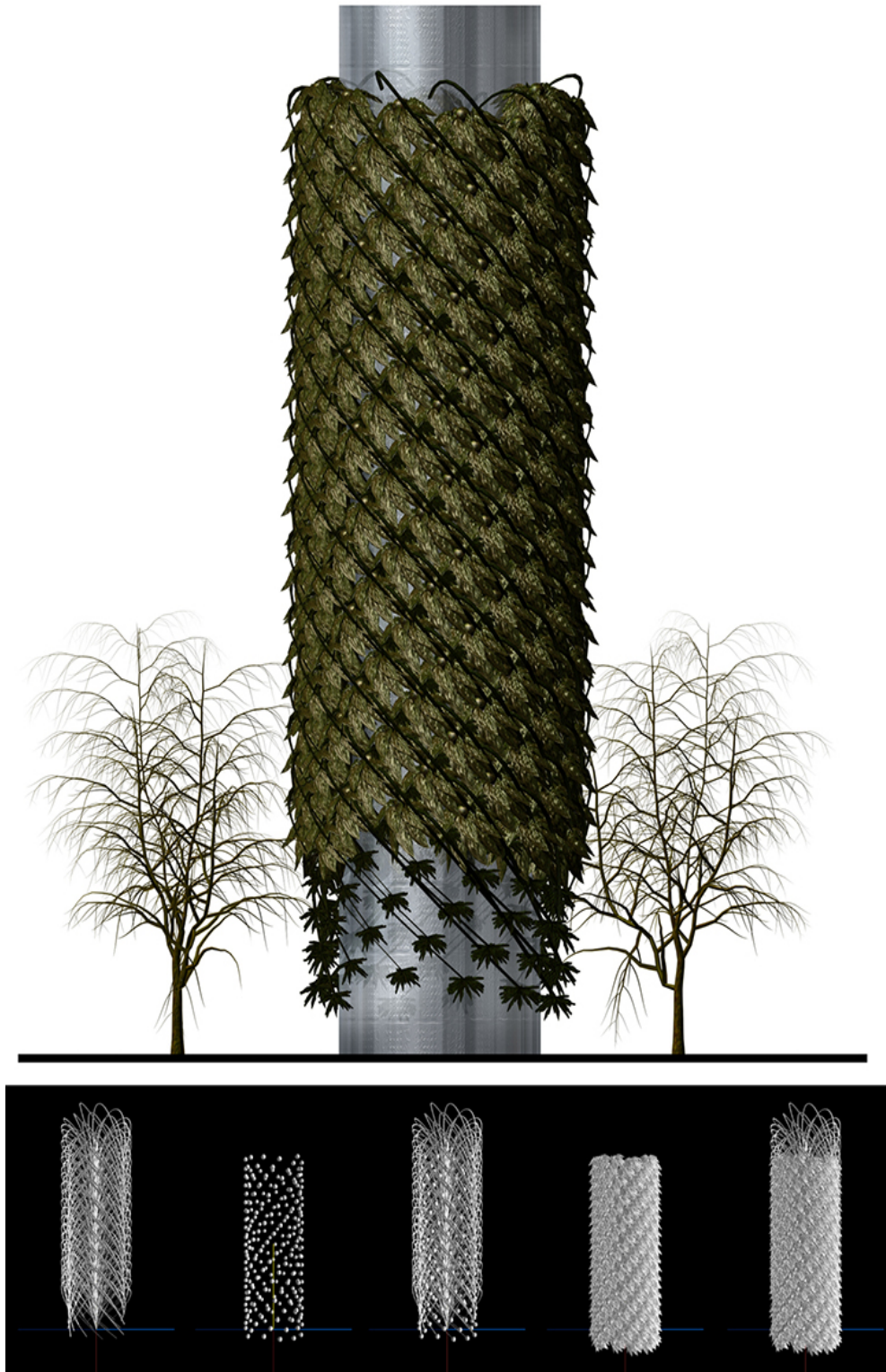


Fig 10a. BioTower. L-Systems and Generative BioAlgorithms. Hypothetical performative leaf panels, activated by metabolic controllers for plantlike filtration and sensor/monitor bioremedial performance. Bottom: Multiple Xfrog-grown trees illustrating, from left to right: branching; housing for digital or metabolic controllers (pods); branching + pods; leaves in closed position; and (far right) branches, pods, + leaves. Xfrog/Rhino/3DS Max. Dennis Dollens.

1.7 • Design Learning: Student Handbook, ALife & Videogames

The Student Handbook, *Autopoietic Architecture: Can Buildings Think?* (Appendix 1), used for Barcelona's Universitat Internacional de Catalunya's (UIC) BioDigital Master studio, spring 2014, sources morphological performances and data adaptation as relevant to observation of nature for generative design operations. The handbook centers autopoietic-extended design as a protocol for research, theory, and practice emphasizing design pedagogy's alliance with complexity science (Davis 2008. Fenwick *et al.* 2011. Wilson 1999) in the sense discussed by Niklas Luhmann in "Complexity and Meaning:"

Meaning can be considered as an evolutionary universal, giving a new and powerful form to the old problem of complexity. Complexity appears as the world — the ultimate horizon (to again use Husserl's terminology) — of other possibilities accessible from every actual experience (Luhmann 1990 80).

Using the OS defined by autopoietic-extended design, students set up conditions for analyzing data extrapolated from objects and nature in order to conduct experiments and generate ideas. The data thus experienced is available for processing as generative computation and may be folded into the students insights and observations to inform their research. From the OS's pedagogical parameters students outline their own research procedures leading to phenomenological input/output readying visual and/or technological data cognitively contextualized and expressed as extended phenotypes (Chapter 5. 5.2) (Dawkins 1982. 1988. Gibson 1986. Langton 1988. Rieffel *et al.* 2013). Data channeled from apps in this process then contributes to networked documentation serving to drive students toward deeper in-field observation that may later be referenced to library, archive, museum, fablab, or laboratory expansion or corroboration.

In order to synchronize digital/analog data with students physically occupying urban or natural locations — sensory aided by smartphones/apps — I consulted videogames and their use as learning models (Galloway 2006. Kirkpatrick 2011. McGonigal 2011. Wark 2007). I see game site and research site correspondence as immersive where student/player tactics have the potential for bringing forth original observation and documentation (Kirkpatrick 2011. Wark 2011). The videogame analogy parallels virtual educational procedures, research tactics, and learning scenarios (Gee 2007) where narrative and design quests reference gaming worlds that many students, according to the Pew Internet & American Life Project, are likely to know:

... for one segment of the population, college students, gaming is virtually a commonplace. Computer, video, and online games are woven into the fabric of everyday life for college students. And, they are more of a social/socializing activity than most suspected (Pew 2003).

Because this assessment is more than a decade old (though still featured among current Pew Research Center publications), I'm cross-referencing it with two new studies. While the newer studies are not specific to college students, survey-demographics closely overlap. A study of "gamification" (Pew Internet 2013) forecasts the importance of digital game strategy in the next decade, and the Pew and Harvard study, "Teens and Technology: 2013," confirms the population's saturation by mobilephones: "Smartphone adoption among teens has increased substantially and mobile access to the Internet is pervasive" (Pew Internet 2013a). "Teens and Technology" further identifies:

Cell phone ownership among teens has been stable since 2011, but smartphone ownership has grown considerably. Some 78% of teens now have a cell phone, and almost half (47%) of those say they have smartphones. That translates into 37% of all teens who have smartphones, up from just 23% in 2011. By comparison, 45% of all adults have a smartphone (Pew 2013 6-7).

These statistics picture technological embeddedness solidifying around general student populations familiar with digital gaming, feature phones (dumbphones), and smartphone mobility (Oxford Internet 2013) — a familiarity that justifies efforts toward university development of e- and m-learning design strategies. I therefore register videogamelike attributes specified in social media and sharing sites for texts, images, and video as models for design learning. With new uses in mind, I also look to an older videogame typified here by PacMan (Wikipedia 2013i) and complement it with the crowd-sourced science webgame Foldit (Parker 2014. Wikipedia 2013l).

In a metaphorical sense, I argue the game-course labyrinth prominent in PacMan (iOS app) is a virtual cartography to be reenvisioned, updated, and transposed (sometimes literally by using a GPS tracking app, for example MapMyRide, Fig 11, p93) in an urban or natural setting chosen by students (Speed 2011). Class work takes place in, and between, digital and real space, where physical places, nature, and objects may be observed/experienced as well as digitally investigated, virtually documented, and researched. The physical territory mapped or tagged with smartphone, app, and GPS is the individual student's research niche (Odling-Smee 1996),

research subject, and theater of operation — all the while remaining physically and experientially accessible. That digital and analog theater may be enhanced with the introduction of additional on- or off-site electronic tools; for example, digital microscopes, sensors, time-lapse video, live-stream video, 3D (handheld) scanning, and fablab connectivity — whose use must accordingly, be recognized as primary sources for capturing and corroborating research data (Lynn 1995. 1999).

The physical-virtual learning territory encompasses objects, organisms, and culturally mediating information open to design analysis and methods imported from cognitive extension (Clark 2008a). This territory may be GPS and communication indexed to other student's sites and evaluated for the tactical and technological data it produces (Heumann 2013. Lynn 1999. Menges & Ahlquist 2011. Speed 2011. Spiller 2009). In this state, the OS displays kinship and precedents that videogame learning (Gee 2007) charted in virtual space as well as in that Conway pioneered with his *Game of Life* (Gardner 1970). It does so expressly as an e- or m-learning tool in the wake of educational sites such as Foldit (2008) and OpenWorm (2013). The Pew Internet study on gamification posted:

Game-like approaches to education and problem-solving are rolling out in new ways. To cite one prominent example, researchers at the University of Washington made headlines in 2011 with their game *Foldit*. It generated a crowd-sourced discovery of the mystery of how a key protein may help cure HIV. The game drew 46,000 participants whose gameplay took just 10 days to solve a problem scientists had been working on for 15 years (Pew Internet 2013).

As we shall see, the analogy of videogames with smartphone-enhanced learning involves generative and evolutionary design rules (Alexander *et al.* 1968. 1977. Heumann 2013. Sullivan 1999) motivating mechanisms of play directed to design, technology, and learning (see also Chapter 7. 7.6). The student's choices may be partially played-out when contingent site conditions impose rules and restrictions from urbanisms or wildernesses that impact solutions for buildings. In cellular automata games and research (Chomsky 1959. Gardner 1970. Heumann 2013. McMulling & Varela 1997. Rieffel *et al.* 2013. Uribe 1981. Varela *et al.* 1974), we likewise find rule transformations determined by neighboring cells thereby having an effect Clark (2008a) describes as environmentally participatory in extended cognition. In Chapter 4 we encounter Sullivan's System displaying the simplest one-to-one example where a drawing cell is understood to generate the next cell in a linear sequence (Top, Plate 2 Fig 15. p157). In Conway's *Game of Life* (Gardner 1970) straightforward environmental rules govern whether



Fig 11. MapMyRide (app) page from the Student Handbook (Appendix 1) for location tracking of specimens for morphological observation, documentation, and idea generation along a route (rich with botanic specimens) supporting in-field morphological research by means of a smartphone. Drawings, mapping, and renderings: Dennis Dollens.

cells live or die (Fig 16, p158 bottom), thus becoming a model of emergent behavior where a cell's neighboring local conditions shape and code individual potential to evolve discrete spaces, systems, populations, and temporal, virtual populations (Davis 2008. Fenwick *et al.* 2011. Uribe 1981. Wolfram 2002). Prusinkiewicz reinforces this cellular evolution bringing in digital biology more fully discussed later around Turing (Chapter 5):

A well-known example of emergence is given by the *Game of Life*, where complex patterns develop in an array of square cells governed by strikingly simple local rules. The development of patterns and forms in the domain of living organisms has been termed morphogenesis (Prusinkiewicz 1994 61 original emphasis).

In this quotation Prusinkiewicz recognizes digital cellular morphogenesis. He takes note of emergence, patterns, and rules as components of morphogenesis. His subject, the *Game of Life*, early on clarified how aspects of digital life — ALife — could demonstrate environmental rules and conditions affecting performance related to neighboring spaces, extended cognition, and technology for modeling digital self-reproduction (Langton 1988. Ray 1994). Autopoietic-extended design, by means of smartphone-to-student augmentation and on-site experience helps students understand such rules, data, and environments. That insight then partners procedural design actions (student ideas) affecting visualization for drawings, models, or programming code guided by the Student Handbook (Appendix 1).

The important relationships between *Foldit*, the *Game of Life*, and Sullivan's *A System* (Chapter 4) is more than associative — all three illustrate rules, morphology, and environments impacting design decisions via directed feedback and recursion. Occupying the environment, observing and studying its conditions by digital and occupational means sets students up to observe, participate, and learn from emergent behavior, rules, and self-organizing procedures. Once organized on-site, student presence and technology creates conditions to generate ideas and spatial experiences not available in classrooms. And, that experience retains the OS pedagogical game-based scaffolding — student site occupation therein actuates rules and tasks involving autopoietic-extended design research unique to students' design intentions.

While I caution that I am not designing a game, I have looked to the literature of digital games as sources for conceptualizing mobile design research (Gee 2007. Kirkpatrick 2011. McGonigal 2011. Wark 2007. Wikipedia 2013). In doing so, I have considered digital game strategies in relation to Sullivan's morphological combinations, Turing's algorithmic plant simulations, Conway's rule set, and autopoietic cellular automata (Gardner 1970. Gee 2007. 2013. Turing 1952. Uribe 1981. Wolfram 2002). From simple rules of gameplay strategy — *go*

there, do that, get this — students cultivate data as contextual and subjectively received and therefore available to be fitted to their projects (Chapter 7. 7.6). The act of student's physical site occupation and first-hand observation of environmental morphology or phenomena intensifies their engaged virtual/physical impressions (input). Those impressions are further intensified with a smartphone's ubiquitous connectivity streaming data or enabling immediate design production via apps (Fenwick *et al.* 2011. Pew Internet 2013. Oxford Internet 2013).

The OS assists students to organize smartphone/app procedures in order to construct analog and digital learning environments; it works in ways akin to videogame worlds attended to by players with hand controllers. It supports learning conditions facilitating the layering of data from nature, biology, urbanisms, or technology for later use in design development. As Kirkpatrick emphasizes in *Aesthetic Theory and the Video Game* (2011), bodily relationships, particularly hand-to-controller actions establish play (directionally tilt-sensitive smartphone games) in dancelike body-to-technology interfacing. Interaction with technology, as Kirkpatrick sees it, fosters a different, less sinister relationship with what used to be called cyborgian prosthetics than that projected in the late-twentieth century (Haraway 1990. Hayles 1999. Wolfe 1998). I see Kirkpatrick's technological interfacing as aesthetically bridging physical and game space as collaborative, gestural, generative, and physically engaged; it thus holds processes in common with smartphone/app use as well as with extended cognition (Clark 2008a. Kirkpatrick 2011 87).

Within the rapidly changing, cognitively challenging focus of videogame play, the temporary thought/thinking/concentration/attention domains *lock-in* (Mason 2008a. b) to engage certain objects, situations, and environments waiting to be cognitively processed by the player/student. Once selected, those objects, situations, or environments must be decoded, distinguished, observed, and predicted in order to communicate (network) between cognition, environment, and on-screen situations — a process Di Paolo (2010) would call sense-making and Clark (2008a) would call extended cognition. Mason might relate them to complexity (see quotation p244) and emergence associated with "*lock-in, path dependence, and internal momentum*" (Mason 2008a 35. 2008b 1 original emphasis).

In episodes of concentration, momentarily focused thought conveys raw data to cognitive domains for subjective processing (Luhmann 1990a) as massively simultaneous acquisition of data nurturing response/output. This self-organizing scenario, considered through a framework of autopoietic-extended design, may be logistically and programmatically configured to support biogenerative architectural research. The gamelike playing field is adaptive (in the player's cognitive construction) to the point from which videogames, digital media, smartphones, and education may be tapped for design strategies. Luhmann explains:

Cognitive systems . . . have only a momentlike existence, as a result of the burden of simultaneity This existence must reproduce itself autopoietically in order to attain stability. . . . They experience the world, therefore, with future and past — that is *duration* — (Luhmann 1990a 71 original emphasis).

This sequence of Luhmann's "momentlike existence," "simultaneity," and autopoiesis extends Mason's "lock-in" (2008b) metaphor of temporary, conceptually permeable cognitive domains bordered by the player's subjective focus as organizational membranes (Maturana & Varela 1980). The experience of such states is testified to by language reflected in everyday speech: daydreaming, trance, wrapped-up-in-play, dead-to-the-world, oblivious, or zoned-out — all indicating intense and isolated states of concentration/focus directed to subjective reverie, environmental phenomena, or object study. In deeply focused states, for example, a person in a daydream may be startled out of a reverie by a warning of danger, nearby action, or noise. The metaphors of everyday conversation revolving around daydreaming I construe as examples where *operationally closed* (Maturana & Varela 1987) autopoietic boundaries function (within entropic nature) and illustrate pathways to an understanding of virtual boundaries constituted for autopoietic-extended design where:

. . . constructive circularity and internal organization (what we call operational closure) is manifested at the levels of the organism and of the nervous system. This neuronal closure specifies a manner of relation to the medium which entails not picking or processing information, but specifying what counts as relevant (Maturana & Varela 1987 253).

By viewing objects and environments briefly and instantaneously conjoined as components of cognitive states in which environmental matter and phenomena contribute input of raw data, I mirror an autopoietic-extended design process exemplified by digital gameplay. As if in a test tube, or in a digital simulation, the simply articulated components of PacMan's virtual world illustrates engagement and procedural experiences — the labyrinth, the chase, the enemy, the avoidance and the success or failure of survival skills and sometimes . . . the reward. In this gameplay, cognitive agent/student and AI-virtual entity (game) operate an autopoietic domain in which the players intensive focus creates a cognitively virtual border or membrane wherein the players lose track of surrounding environments and non-game action — a kind of deep focus *lock-in* (Mason 2008a. b.) discussed above. (See Chapter 2. 2.2 p122 referencing *Wasp and Pear*

and *Breakfast*). With the peripheral world temporarily ignored, non-essential data flow is blocked in favor of ongoing game feedback cultivating deeper player motivation and hence game (AI) self-production. I think this process is reproducible for learning via autopoietic-extended design.

In terms of gamification, understanding cognitive lockout as directed concentration/focus has only recently began to reverse negative connotation of being addicted to videogames and/or smartphones (McGonigal 2011). Here I welcome similar levels of gaming deliberation where the student/player is concentrating on a technologically engaged environments requiring sensory-motor investigation with rulelike (*go there, do that, get this*) adherence/avoidance pinpointed to design generation. In this way game skills transfer to digital research skills in this smartphone enabled OS (Gee 2007. McGonigal 2011). This player, student, data, and environment relationship then bases e- and m-learning on experience where the Pew Internet and American Life Project (2003) found, for "one segment of the population, college students, gaming is virtually a commonplace" (Oxford 2013. Pew Internet 2013).

Basic rules of gaming expressed as *go there, do this, get that* — or more pointedly *go there, don't get eaten, survive* — convey evolutionary tactics for nurturing data from experience (actions) organized around processing possibilities of digital software and apps. Autopoietic-extended design in hybridized learning environments mimics strategies like those of videogames at an organizational level — blended physical/virtual occupation — through which smartphones and apps support the observation of nature and cities to cultivate design data. The architectural task of acquiring data from nature to generate ideas in a virtual/physical field borrows gamification tactics coordinated with class program, design objective, research potential, and communication apps to place pedagogical development and student's use of smartphones on a playing field. Some gamelike and/or social medialike conditions and properties apply in autopoietic-extended design configured as:

- 1) Fusing analog/digital spaces, organisms, environments, objects with data to support hybridization involving animate, inanimate, and biotechnological systems where architectural sensing and performative operations bridge biology, nature, matter, and living technology to design.
- 2) Prescribing how to interface humans, objects, technologies, and environments as symbiotic (nondualistic) in order to emphasize bioremediation modeled from decoded nature and interpreted for autopoietic design performance.

- 3) Mediating and engaging cognition with nature through technology for cognitive and perceptual data selection resulting from in-field occupation, participation, and observation.
- 4) Distinguishing living, cognitive, and non-cognitive input/output in relation to objects, environments, life, plants, and intelligence in order to inform and visualize the hybridization of animate and inanimate functions for buildings and materials.
- 5) Harvesting and formatting environmental data for biodigital research leading to the prototyping of experimental metabolic design based on computational simulation and biomechanical materialization.

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1.8 • *Autopoiesis* and Living Technology

"Autopoiesis: The Organization of the Living," (Maturana & Varela 1980) introduces theory constructs to plot minimal biological requirements for life and, to some extent, social systems (Luhmann 1990a. Maturana & Varela 1980. Schumacher 2011). For architecture facing questions such as "Can buildings think?" autopoietic theory offers metabolic performance markers to identify degrees of intelligence (bacteria, plant, animal, or computer) necessary to design autonomous behavior capable of bioremedial chores in buildings.

And, autopoiesis leveraged within extended cognition, supports the exploration and communication between domains of metabolic and living technologies for bio-performative buildings. (Bedau *et al.* 2013. Clark 2008a. Di Paolo 2005. 2008. Maturana & Varela 1980. Weber & Varela 2002). "In these cases," Clark and Chalmers (1998 29) write, "the human organism is linked with an external entity in a two-way interaction, creating a coupled system that can be seen as a cognitive [autopoietic] system in its own right." Still, to be metabolic *and* autonomous, architecture needs actuating environmental intelligence — living technology — as autonomous systems mediating the environment. Soren Riis notes:

... living technology manifests a crucial dependence on the elementary self-unfolding of nature ... It is the astonishing and autonomous autopoiesis of nature that grants the possibility of living technology (Riis 2013).

More pragmatically, Bedau *et al.* defines living technology:

When the scientific and technological fruits of artificial life are embodied in technology with real practical use, sometimes the result can properly be called *living technology*. ... Living technology is most simply defined as technology that is alive, but it is convenient

to require that such technology furthermore be useful because of being lifelike and not be a simple variant of existing life. We will call something *lifelike* if it has one or more of life's characteristic properties. . . . Every life form (i) autonomously creates a boundary distinguishing itself from its environment, (ii) autonomously sustains itself through the synthesis of building blocks by harvesting energy and raw materials from the environment, and (iii) autonomously reproduces itself and evolves, through inheritance with variation of reproducible internally stored information that can activate and control the life form's crucial functions (Bedau *et al.* 2013 original emphasis).

Autopoiesis, with its organizational breakdown of components, unities, and domains expressed in theory, is metaphorically speaking, a manual for gauging minimally proscribed rules, hierarchies, recursivity, self-maintenance, self-production, and structural coupling in organisms, living technologies, and environments. The three points noted in the above quotation by Bedau *et al.* (2013) are essentially a recap of Maturana and Varela's (1980) theory. Varela later described what he called the "paradox proper to autonomous identity: the living system must distinguish itself from its environment while at the same time maintaining its coupling:"

In defining what it is as unity, in the very same movement it defines what remains exterior to it, that is to say, its surrounding environment. A closer examination also makes it evident that this exteriorization can only be understood, so to speak, from the "inside:" the autopoietic unity creates a perspective from which the exterior is one, which cannot be confused with the physical surroundings as they appear to us as observers (Varela 1997 78).

With the distinction between interior organism and environment, a working definition of "coupling" (structural coupling) is in order. I return to coupling in more detail later (Chapter 7. 7.3) but temporarily, it is "a symmetrical concept whereby system and environment influence each other" (Di Paolo 2008 15). Through structural coupling — components, unities, borders, membranes, and domains — interact with each other to create metabolic agents and/or living individuals, for example a biological cell. Defining biological functions via component interactions makes autopoiesis unique "among self-organizing concepts" (Weber & Varela 2002 116) because, in defining what is metabolic — a prokaryotic cell perhaps — by default, requires describing life, intelligence, and degrees of cognition. With minimal definitions of life and cognition we can speculate how to create architecture as intelligent machines (Turing 1950).

The cleverness of biological autopoiesis (Maturana & Varela 1980. 1987. Varela *et al.*

1992) emanates from rule-sets and their operational requirements that, when met, define whether or not a subject is metabolic. As we heard earlier, Jonas (1966) considered metabolism a key dialectical element, where all living things are metabolic and no nonliving thing is. When operative, autopoietic-extended design can facilitate coupling with the autopoietic rule-set as a theoretical machinic through which agents and environments may be recognized, categorized, and brought together as metabolically affinitive and, on occasion, as living technology (Bedau *et al.* 2013. Gibson 1986. Maturana & Varela 1980 82-83. Wells 2002). When agents and environments are recognized, categorized, and brought together they may also be programmed for tasks and thereafter prototyped as metabolic elements for biogenerative architecture.

In an example of "environmental coupling" Di Paolo explains an extended phenotypelike process (Dawkins 1982) in which boatman water spiders intentionally construct and transport air bubbles for survival underwater. "The mediation," (the air bubble) according to Di Paolo, "is so intimately connected with vital functions that the [spider's] living system itself might be called extended" (2008 17). Yet, other animals display similar extensions, and to a degree, I suggest structural coupling and Clark's parity principle (Chapter 7) as interchangeable theoretical devices (coupling-parity) for viewing animal-built structures (here the air bubble) as extended phenotypes (Dawkins 1982).

Using site/object monitoring and extrapolation, the coupling-parity process involved in recognizing metabolic components and extended phenotypes can help students postulate animal/human technology and construction in logical (Corbett 1971. Toulmin 1984) terms Di Paolo (2008 17) posits with the spider's "environmental coupling." In turn, I contend that architecture today is many (toxic) degrees away from an ideally metabolic state but is, ultimately only theoretically intelligible in a context of cognition, living systems, and nature (Gibson 1986. Jonas 1966. Odling-Smee 1996. Odling-Smee *et al.* 2013).

Organism/niche congruence (Maturana & Varela 1980 11), like that exhibited by the boatman spider or those we see later with crickets and seedpods, illustrates structural- or environmental-coupling in which nature and constructed objects may be recognized as cognitively bound to metabolizing organisms and inseparable from life processes (Clark 2008a). Maturana and Varela are here clear on man-made, synthetic living systems as capable of embedding metabolic attributes:

In practice, it is accepted that plants and animals are living but their characterizations as living is done through the enumeration of their properties. Among these, reproduction and evolution appear as determinant, and for many observers the condition of living appears subordinated to the possession of these properties. However, when these

properties are incorporated in a concrete or conceptual man-made system, those who do not accept emotionally that the nature of life can be understood, immediately conceive of other properties as relevant and do not accept any synthetic system as living by continuously specifying new requirements (Maturana & Varela 1980 83).

To my knowledge, few people consider “synthetic systems as living” or animal constructions (including human architecture), as expressions of life properties. In the domain of niche construction “enumeration of their properties” brings to mind animal architecture as extended phenotypes (Dawkins 1982. Hansell 2005. Odling-Smee 1996. Odling-Smee *et al.* 2013). And extended phenotype in the context of *Autopoiesis: The Organization of the Living*, is inseparable from “a prediction of a niche,” configured below from Maturana’s Introduction:

Thus for every living system its organization implies a prediction of a niche, and the niche thus predicted as a domain of classes of interactions constitutes its entire cognitive reality (Maturana & Varela 1980 11).

Herein, Maturana implicitly acknowledges prediction in cognitive/environmental realms with implications for architecture and extended phenotypes embedded in cognitive-niche production — a subject I relate to AI and computation in Chapter 5 and to Turing’s *genetical search* (p111), and more fully address in Chapter 7 (Clark’s predictive functions for cognitive extension).

In upcoming case studies referencing structural coupling and niche construction (building), I suggest routes for autopoietic-extended design to aid students configure and recognize tools, objects, and architecture as extended phenotypes (Chapter 7. 7.5) (Clark 2008a. Dawkins 1982. Di Paolo 2008. 2010. Hansell 2005. Odling-Smee 1992. Odling-Smee *et al.* 2013). In turn, tools as extended phenotypes establish theoretical and operational pairings amenable to extended cognition (Hansell 2005 194). Maturana gives a phenomenological interpretation:

... we human beings exist in structural coupling with other living and not living entities that compose the biosphere in the dimensions in which we are components of the biosphere (Maturana 2002 27).

Autopoietic-extended design herein defines temporary unions of animate beings with inanimate matter, extended-phenotype constructions, and objects that under limited conditions may be coupled components of metabolic systems — some with aspects of life and/or cognition.

Cognition is sense-making in interaction: the regulation of coupling with respect to norms established by the self-constituted identity that gives rise to such regulation in order to conserve life (Di Paolo 2008 19).

Nagel weighs in with:

The question is how to understand mind in its full sense as a product of nature — or rather, how to understand nature as a system capable of generating mind (Nagel 2012 72 loc915)

Di Paolo's (2008 19) assertion defines cognition/sense-making as one means of autopoietic extension. Nagel (2012 72) places cognition/mind in the context of a force of nature, in which case, self-maintenance and self-production are critical to living systems as required by autopoiesis (Maturana & Varela 1980). When considered in scaled terms of single-cell organisms or multicellular plants (all capable of sense-making), Di Paolo's defined cognition-sense-making, as used here for buildings, constitutes a pathway for the investigation of nature where intelligence need not be factored in human terms (See Turing 1948. Chapter 5. 5.2 p202). Daniel Dennett, explaining Turing's view of machine intelligence, said: "his point was that we should not be species-chauvinistic, or anthropocentric, about the insides of an intelligent being" (Dennett 1998 13) and this may equally be applied when investigating, Can buildings think?

Architectural intelligence, like machine intelligence, may be envisioned as life without consciousness. According to Maturana: "congruence between an organism and its niche" (2002 26) follows basic autopoietic logic without anthropocentric limitations to intelligence (Maturana & Varela 1980). If we place architecture in the role of an organism and then recognize it for advanced architectural research, we may then find "congruence between an organism and its niche," as a position to devise bioremediation through metabolic components of buildings.

What might be recognized as recursive scaling, Maturana addresses as layered systems of life/environments where the niche of a cognitive agent is made up of feedback relationships with composite cellular systems. This is explained:

The society of bees . . . is an example of a third order self-referencing system . . . it has a circular organization superimposed on the second order self-referencing system that are the bees, which in turn have a circular organization superimposed on the first order living systems that are the cells; all three systems with their domains of interactions are

subordinated both to the maintenance of themselves and to the maintenance of the others (Maturana and Varela 1980 11).

The oversight above was not to include the hive. The hive as an extended phenotype (Dawkins 1982. Hansell 2005) without which (many) bee societies cannot be organized requires explanation through autopoietic-extended design in order to recognize the animals' architecture as cognitively active, environmentally dynamic, and able to implement metabolically necessary chores (Turner 2000 2 & 187). Maturana text is at first stable:

... all three systems with their domains of interactions are subordinated both to the maintenance of themselves and to the maintenance of the others ... (Maturana & Varela 1980 11).

But this I suggest is incomplete and requires expanding to continue (in my words):

... including the constructed physical architecture manifested biologically as the hive with its own rules, environmental interface, organic performance, and its metabolically legislated maintenance.

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1.9 • Architecture = Nature

By means of smartphone ubiquity and functionality (Pew Internet 2013), pocket-sized computers now act as mediators between cognition and environments — in one sense they are units of co-intelligence meeting the anticipations of earlier visions of cyborgian futures (Clark 2003. Clarke & Hansen 2009. Haraway 1990. Hayles 1999. Wolfe 1998. 2010). Informally looking to streetscapes, airports, and cafes I concluded that Android and iOS are the smartest, most commonly available and omnipresent AI constructions — machines — at hand. In the U.S. cellphone ownership was tagged at over 90% of the adult population by the Pew Research Center (2013). Cellphone, but particularly smartphone high performance, advanced materials, sensors, and artificial intelligence make surrounding buildings seem dull, dimwitted — designed for an age long past. For design learning and research, smartphones should be better-integrated data-tunneling devices sensing and enabling environmental *tuning* (Coyne 2010). They connect material, algorithmic, and phenomena for design research. In essence, social networks facilitated by smartphones establish compelling models for virtual classes and participatory learning spaces.

From the perspective of autopoietic-extended design — cognition, technology,

environment, and architecture are naturally occurring, collaboratively unified, and inseparable-life participants recursively generating knowledge-facilitating data. From "The Cognitive Program of Constructivism:"

A process is called "recursive" when it uses the results of its own operations as the basis for further operations — that is, [when] what is undertaken is determined in part by what has occurred in earlier operations. In the language of systems theory . . . one often says that such a process uses its own outputs as inputs (Luhmann 1990a 72).

This iterative process is capable of stimulating ideas metabolized from data first perceived and/or delivered via direct observation and/or technology as input. Relying on the mechanisms of autopoietic self-organization (Weber and Varela 2002) we may outline research processes to nurture self-organization by directing technological observation and analyzing the data it returns. Design research and the situations it generates may then be constructed for learning following requirements outside of traditional design expertise that subsequently identifies ways to fold-in multidisciplinary collaboration (Clark 2008a. Maturana & Varela 1980).

To support my contention that *architecture is part of nature*, I have formulated a syllogistic proposition (Corbett 1971. Toulmin 1984). The syllogism braces the autopoietic-extended design OS emerging in these pages:

All life is embedded in nature,
All architecture is embedded in life, therefore
All architecture is embedded in nature.

Initially the syllogism appears banal — from its premise anything and everything is part of nature — but things synthetic are not generally constituted as natural. Nevertheless, synthetic things, particularly synthetic life and living technology (Bedau *et al.* 2013), are intimately related to biogenerative architectural materialization and systems I discuss (Armstrong 2012. Armstrong & Spiller 2010. Cronin 2011). What I programmatically emphasize in autopoietic-extended design is a synthesis of design/nature and a biomimetic perspective that toxicity must be reprogrammed for lesser (or zero) environmental impact and that even so-called artificially fabricated materials are part of human nature and reformable. Thinking of toxic products/buildings as outside of nature — as artificial — gives them apologetic cover as foreign

and *other*. Under these considerations the syllogism is far from banal; it embeds the idea of corrective (intelligent) acts related to buildings' performance.

Furthermore, the syllogism counters mind/body, mind/nature, toxic/nontoxic, and real/artificial dualisms (Gibson 1986. Jonas 1966) to support autopoietic requirements elaborated for learning and research. *Student + technology + environment*, as an autopoietic unity, lies within the general domain of nature and functions by conceptually integrating physical, cognitive, and phenomenological systems in a biologically-related design research process (Jonas 1966. Luhmann 1990a. Maturana & Varela 1980).

"We are now at the point where we can see the historical reversal of the Cartesian relationship between the machine and organism" (Canguilhem 1992 56) and may construct alternative realities based on Maturana's construction of species reality (Hayles 1999. Lettvin *et al.* 1959). Following on the above syllogism, I suggest the relevance of Di Paolo's definition of organism vis-à-vis matter:

If living systems are part of nature's ontology, and if they constantly depend on matter at a given time, but are not attached to a specific collection of particles through time, then their relation to matter, and so to the laws that govern matter, is one of need on the one hand and freedom on the other. Organisms are a wave of matter and energy, they are bound by the laws of physics but not fully determined by them as their destiny is not attached to any particular material configuration but they ride from one configuration to another. Jonas argues how this relation of needful freedom starts with metabolism but is later exploited and expanded by evolution in animals and eventually in humans (Di Paolo 2010 139).

A student or designer exists in relation to metabolic systems in the environment and practices design from them by constructing systems. Di Paolo's (2010 139) "wave of matter and energy," considered with the preceding syllogistic logic, links requirements of autopoietic unity with animate properties that also concern the production of design and infrastructural systems. I factor in learning as a domain of living systems but contend that not all learning systems need to be metabolic — AI and algorithmic learning, for example. In this respect, autopoietic-extended design is machinic (Chapter 2) as Canguilhem, sounding autopoietic, notes:

... a tool or a machine is an organ, and organs are tools or machines (Canguilhem 1992 55).

Jonas continues with a related process of visualization and making and, hence, of tools "basic to the modern conception of knowledge" (1966 202), thereby addressing nature, conceptualization, and construction as relevant to autopoietic-extended design in terms of Di Paolo's sense-making (Di Paolo 2005. 2008. 2010). Jonas writes of the multiplicities in nature he considers cognitively generative as recursive and retrievable, but unlike:

... substantial natures, distributions of conceptions [design ideas] can be reconstructed, even freely constructed, in mental models and so allow of understanding. Again, unlike "natures," they may be actually repeated or modified in human imitation of nature, that is in technique, and so allow of manipulation [architecture]. Both understanding and making are here concerned with relations and not with essences. In fact, understanding of this sort is itself a kind of imaginary making or remaking of its objects, and this is the deepest cause for the technological applicability of modern science (Jonas 1966 202).

To a large degree, Jonas's conceptualization encapsulates the intention of biodigital site research in a process like that of Di Paolo's sense-making. For autopoietic-extended design a component of sense-making is inspiration-making, the working through nature to extrapolate ideas from data for design (Weinstock 2006a 27). Jonas's (1966 202) statement: "distributions of conceptions can be reconstructed, even freely constructed, in mental models and so allow of understanding [of nature]" may then be read to open organism/environmental cognition to cultivation. His concept allows the rooting of design intention and ideation within perception and cognitive extension to anchor them as mutually contingent in nature.

Jonas writes in the spirit of unifying comprehension, technology, and nature when he ventures: "the distinction between natural and artificial, so basic to classical philosophy, has lost its meaning" (Jonas 1966 203). That dichotomy — natural/artificial — is also challenged when we read (Chapter 6) concepts of individual minds disputed in favor of distributed intelligence (Gosden 2005. 2010), or hear of the house recast as a machinic object vis-à-vis Le Corbusier (2007). The above syllogism then buttress the stand against the dichotomies of nature/artificial and mechanist/vitalist to remind students: *all architecture is embedded in nature*.

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2.0 • Extended Cognition

Challenging notions of cognition as purely brain/body phenomena, Andy Clark and David Chalmers advocated views of distributed, collaborative environmental perception and sensory-data sourcing as extended mind or extended cognition. Their 1998 paper, "The Extended Mind," still reverberates in philosophy and cognitive science, stressing: "Cognitive processes ain't (all)

in the head!" (Clark & Chalmers 1998 29). In parallel, they offered a sound-bite brief — but nevertheless critical question: "Where does the mind stop and the rest of the world begin?" (Clark & Chalmers 1998 27). Toward an answer, they offered:

[T]he biological brain has in fact evolved and matured in ways which factor in the reliable presence of a manipulable external environment (Clark & Chalmers 1998 31).

From Niklas Luhmann we later hear:

Cognition is neither the copying nor the mapping nor the representation of an external world in a system. Cognition is the realization of combinatorial gains on the basis of the differentiation of a system [the brain] that is closed off from its environment (but nonetheless "contained" in that environment) (Luhmann 1990 69).

Consequently, I locate pedagogical activity and generative design — following Clark from *The New York Times* — as partially *out-of-our-brains* (Clark 2010b) and partially distributed in the habitable, sensory realms of forces, matter, minimally cognitive life (bacteria for example), and nature. Additionally, acknowledging sentience, John Stewart writes:

[E]ven the most primitive living organisms are minimally "cognitive" . . . [and the] most elementary sort of cognition does not have the form of propositional knowledge, knowing "that;" it is not even knowledge "of" well-defined objects; rather, it is a sort of "how" that is intrinsically tacit (Stewart 1995 318).

Communication takes place at sensory levels basic to cognition as well as through spatially charged autopoietic and extended cognitive domains. These domains transport data to varying forms of high- and low-order cognitive processes. From the human-engaged *sticks* Clark (2008a) investigates, to videogames (Parker 2014), and potentially cognitive cells and plants (Brenner *et al.* 2006. Calvo Garzón 2007. Darwin & Darwin 1881), perceptible and configurable data engages and transforms life and cognition. Stewart (1995) distilled this autopoietic formulation as:

cognition = life

All metabolic sense-making, from bacterial to human, demonstrates intelligence through communication, recognition, and engagement (Adamatzky 2013. Clark 2001. 2008a. Di Paolo 2008. Margulis 1999. Maturana & Varela 1980. Stewart 1995). Surrounded in a world where robots, drones, and smartphones are taking on animal and insect performance, I see every reason to direct design learning and research toward prototyping metabolic buildings (Armstrong 2012. Floreano & Mattiussi 2008. Webb 1996. 2009. Webb & Consi 2001).

After Clark's "Re-Inventing Ourselves" (2007a), *Supersizing the Mind* (2008b) argued that mind functions are distilled from objects as cognitively-engaged things, agents, and tools. Mind functions further build circuits that support predictive thoughts and actions (Clark 2012. 2013. 2013a). In *Supersizing the Mind*, Clark explains one type of cognition-to-object circuit as an environmental interface:

... where the extended system "biological-agent + stick" meets the rest of the world
(Clark 2008b loc 888).

"Biological-agent + stick" situates both the physical user and the object as autopoietic. The consequent autopoietic unity might read: *agent + stick + environment*. In "Re-Inventing Ourselves," Clark had already identified complexity at the agent-to-object junctures:

In these cases there suddenly seem to be two interfaces at play: the place where the stick meets the hand, and the place where the extended system "biological-agent + stick" meets the rest of the world (Clark 2007a 265).

Hacking Clark's "biological-agent + stick" as *biological-agent + smartphone* does not distort his example since digital tools may activate, sense, and communicate environmental extension. The subtler point is: the tool at some moment, for some duration, becomes a cognitively indispensable, indistinguishable, or inseparable conveyor of perception in union with thinking, and a smartphone easily fits this role as "interface." People who wear glasses or contact lenses could assent to: one loses awareness of the mediating lenses in fully perceiving the field or subject of vision. Similarly, few of us consider the network interface or sensor infrastructure when using smartphones.

The stick/smartphone are not stand-ins for other tools; they are, rather, cognitive-state objects extending perception. Clark's amalgam of "stick-augmented perception," (2008b loc 887) encapsulates a first-level fusion where an object becomes a mediating layer or circuit to aid thinking through environments. "Re-Inventing Ourselves" (2007a), and *Supersizing the Mind*

(2008a. b), articulate how "biological-agent + stick" (or smartphones and apps here) engage data by becoming circuitry in extended cognition. Paralleling autopoietic-extended design's unity of *student + technology + environment*, "biological-agent + stick" embodies and illustrates the coupling (Maturana & Varela 1980 108) of animate and inanimate life where the cognitive boundary is itself of cognitive manufacture. This unity of cognitive circuitry parallels some gameplay conditions relevant where play and narrative feedback to domains both organizational and performative through the OS (Chapter 7. 7.7).

The autopoietic-extended design OS then embraces autopoietic theory to activate mechanisms for structurally coupling different domains of perception, matter, and nature where "autopoietic systems can couple and constitute a new unity. . . . [and, where after] the autopoietic system thus generated is a unity in the physical space . . . a living system" (Maturana & Varela 1980 108-109). In 2002 Maturana more definitively defined structural coupling:

The relation between a living system and the medium [environment] in which it exists is a structural one in which living system and medium change together congruently as long as they remain in recurrent interactions. I have called this relationship structural coupling (Maturana 2002 24).

Clark's investigations impacts structural strategies for autopoietic design and research by articulating possible roles and routes that are usable to generate design where cognitive functions seek data and phenomenological input from physical objects and environments. If Clark's theory thus collaborates with autopoiesis, the two may then be synced to pool resources for identifying and understanding mechanisms of living and non-living systems. Observing, examining, and extrapolating from environmental systems via autopoietic-extended design thus enables insight and propositions for form-finding relating to biocomputational and metabolic building performance (Clark 2008a.b. Di Paolo 2008. Maturana 2002 24. Maturana & Varela 1980).

Autopoietic-extended design then constitutes a scaffold upon which students may investigate metabolic functions and/or bio-intelligence in order to generate architecture (Chapters 6. 7. Appendix 1). By conceiving of architecture in a line of machines compatible with those Turing (1950. 1951) referenced in: "Can machines think?" I frame questions concerning types and modes of intelligence and metabolic processes as issues for architectural experimentation (Bedau *et al.* 2010. Langton 1988. 1996. Saunders 1992. Wells 2004. 2006). Additionally, by interfacing machines and architecture, Turing's (1952. 1954) morphogenetic

projects and their associated biological computations become precursors to, and starting points for, generative architecture.

Analyzing Turing's simulation programming, drawings, and computer graphics as mediators between technology, nature, and code refocuses history as a present-day scrim (Brenner 2012. Cooper 2012. Dyson 2012a b. Reinitz 2012). Turing's drawings also illustrate pattern development expressing biological growth and scaling consistent with extended phenotypes, witnessed in his (Figs 23-27, pp187-191) fircone, daisy, or computer graphics (Dawkins 1982. Odling-Smee 1992. Odling-Smee *et al.* 2013. Swinton 2004. 2013. Turing 1952. 1953). At this point I briefly introduce Turing's morphogenetic research (Chapter 5) to enable reader connections (*Nature* 2012. Kondo & Miura 2010). From *Bio-Inspired Artificial Intelligence* we hear:

[T]he phenomenon of *morphogenesis*, that is, the robust generation of complex forms and patterns starting from embryos . . . appears at first look to be quite homogeneous. In 1953 Alan Turing, using a simple mathematical model, showed how patterns can emerge spontaneously by amplification of small fluctuations in an otherwise homogeneous structure . . . Turing proved that — given the right equations of the chemical reactions and the right values for the diffusion parameters — after some time the concentrations of the chemical substances forms wavelike or spotlike *Turing Patterns* . . . (Floreano & Mattiussi 2008 320-321 original emphasis) (See also Fig 28, p192).

To summarize:

- 1) Turing's reaction-diffusion, symmetry-breaking, algorithms sourced in nature lead to biological, embryological, and environmental computer simulations (Copeland 2012. Copeland & Proudfoot 2004. Reinitz 2012).
- 2) Clark's vision of extended cognition accounts for environment-to-cognition co-generative communication (Clark 2008a. 2013a).
- 3) Maturana and Varela's (1980) autopoiesis provides a system to define minimal-state living, sense-making organisms in nature (Di Paolo 2005).

I shall unpack these three points in the chapters that follow. For now they schematically support the workings of autopoietic-extended design formulated as a pedagogical OS. That OS is intended to help students manifest, in physical and digital realms, procedural and ontological sources for design ideas and projects in support of biogenerative architecture and design learning.

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In this facilitation, I identify compatibilities where Turing's late work may be looked at from Weber and Varela's (2002), and Di Paolo's (2005. 2008) view of "engagement of a system with its world" (Di Paolo 2008 12). Christof Teuscher's (2004) research supports that view. Teuscher uncovered in Turing's (1948) "Intelligent Machinery," the rudiments of search algorithms and prediction functions that imply research "engagement of a system with its world." And those prediction functions are pertinent here to Clark's (2012. 2013. 2013a) recent research. I then seek to harness (for classes and within the OS) such pertinences for biodigital and metabolic design identification and prediction where:

... the brain tries to predict the current suite of cues from its best models of the possible causes. ... [that] by our own actions, help to bring the new stimulus about (Clark 2013a 182 & 188).

Pairing Teuscher's (2004) findings to learning via "engagement of a system with its world" (Di Paolo 2008 12), I suggest Turing may have contemplated rudimentary algorithmic thought processes using search and prediction referenced to experiments with control systems and switching for thinking machines. In "Artificial Life," Harvey, Di Paolo, Wood, Quinn, and Tuci state in relation to evolutionary robotics/control systems, that "... Alan Turing talked of designing brainlike networks through 'genetical search'" (Harvey *et al.* 2005). Further, speculation by Teuscher suggests: "Turing was probably ... the first person to propose a sort of *genetic algorithm* — which he called *genetical* or *evolutionary search*" (Teuscher 2004 500 original emphasis). Teuscher associates Turing with the early development of AI and genetic algorithms as do, Floreano and Mattiussi (2008). Teuscher quotes Turing:

There is the genetical or evolutionary search by which a combination of genes is looked for, the criterion being survival value. The remarkable success of this search confirms to some extent the idea that intellectual activity consists mainly of search (Turing 1948 in Teuscher 2004 500).

If "genetical or evolutionary" search leading to predictive algorithms is rudimentary, it nevertheless merges period tenor and dates Turing's concepts with his little-understood and unfinished late biological research (Turing Digital Archive 2014). That unfinished research may have been in support of developing procedures and code to program Manchester's "Baby" and Mark I computers and his later translation of biological attributes into computational code and machine simulations (Eberbach *et al.* 2004. Prigogine & Nicolis 1967). Further, investigating genetical search may have helped him conceptualize his (1950a) writing and coding for Manchester's *Programmers' Handbook* (Cooper & van Leeuwen 2013. Copeland 2012. Hodges 1992. Lavington 2012 42. Richards 2005. Rooney 2012 14). In Chapter 5 I more fully consider the delayed influence of Turing's (1936. 1948. 1950. 1952. 1953) theoretical conceptualizations in order to clarify his impact on biodigital and generative architecture. For now, using Dennett's words we may establish, Turing as:

... one of the principal inventors of the computer. ... It was he who first figured out, in highly abstract terms, how to design a programmable computing device — what we now call a universal Turing machine. All programmable computers in use today are in essence Turing machines (Dennett 1998 2).

Turing publically discussed what is essentially today's evolutionary computation (Floreano & Mattiussi 2008. Harvey *et al.* 2005. Markoff 2014. Ray 1994) and aspects of AI in a 20 February 1947 lecture to the London Mathematical Society (Eberbach *et al.* 2004 165) when he considered evolved, mutating computation that results in emergent intelligence:

Let us suppose that we have set up a machine with certain initial instruction tables [programs], so constructed that these tables might on occasion, if good reason arose, modify those tables. One can imagine that after the machine has been operating for some time, the instructions would have altered out of all recognition, but nevertheless still be such that one would have to admit that the machine was still doing very worthwhile calculations. ... When this happens I feel one is obliged to regard the machine as showing intelligence (Turing 1947).

After leaving the NPL for Manchester (1948), Turing made the transition to morphogenetic drawings, botanic programming, and computations for intelligence in fields now recognized as AI and ALife (Bedau 2003. Copeland 2012. Eberbach *et al.* 2004. Hodges 1992. Swinton 2004. Teuscher 2004). Thereafter, his 1936-1947 work became the bedrock for his

early-1950s thinking leading to the drawings, digital simulations, and algorithms discussed in Chapter 5.

In the mid-1960s Aristid Lindenmayer outlined a method to simplify Turing's "mathematical complexity of first- and second-order differential equations," replacing them with "finite mathematics" that, consequently lent L-systems:

... more readily [available] to combinatorial manipulations, such as programming for digital computers, [where] the theoretical framework can be kept at a rudimentary level (Lindenmayer 1968 302-301).

Jonathan Swinton (2004 494) found later that Veen and Lindenmayer also used reaction-diffusion equations in the 1977 programming of a computer model that subsequently: "generates most of the phyllotactic patterns observed in nature" (Veen & Lindenmayer 1977 127). The reaction-diffusion equations thus bridge Lindenmayer and L-systems directly to Turing, and Turing directly to later computational generative systems still in use for landscape and plant generation as well as film animation. Here, Figs. 6-10a (pp76-89) illustrate Xfrog's use of L-systems for experimental biodigital architecture completely generated from digital-botanic trees. (To note: Xfrog as of August 2014 is in the running for a Scientific Achievement Oscar as a "System for modeling, animation, and rendering of digital vegetation" Xfrog 2014).

Holding aside Lindenmayer's Turing-dependent research for a moment, we read Reinitz (2012 464): "[the] heart of pattern-making is symmetry-breaking," and that Turing: "created a nonlinear system by turning on diffusion discontinuously in an otherwise linear systems." Two years before Reinitz, Japanese scientists reported breakthroughs in understanding the formation of biological patterns by using Turing's model. They wrote in the journal *Science*: "the reaction-diffusion model proposed by Alan Turing is a masterpiece . . . explain[ing] how spatial patterns develop autonomously" (Kondo & Miura 2010. Sheth *et al.* 2012). For perspective, Prusinkiewicz writing in *Artificial Life* considered patterning in technical and generative terms:

Reaction-diffusion models were developed by Turing to explain the "breakdown of symmetry and homogeneity," leading to the emergence of patterns in initially homogeneous, continuous media. The patterns result from the interaction between two or more morphogens [chemicals] that diffuse in the medium and enter into chemical reactions with each other (Prusinkiewicz 1994).

Turing's unfinished research leaves strong evidence for his having considered relations between nature and computation, not only for programming, but also for biological simulations related to cognition, embryology (Richards 2013/1954. Turing 1953), and AI whose computational processes tackled digital visualization and generative simulation that I soon return to (Prigogine & Nicolis 1967. Turing 1950. 1952. 1953). Framing the above concatenations between nature, intelligence, and computation as impacting design, and then searching methods for learning from them, helps setup conditions to consider Louis Sullivan's (1999/1924) pedagogical, *A System of Architectural Ornament* (Chapter 4), as a precursor to generative, rule-based architecture. And, finding Sullivan's *System* pre-digitally generative, positions *A System's* transcendental call for living architecture and its morphological drawing lessons, for comparison with Turing's morphogenetic drawings, simulations, and programming as intellectually complementary to each other (Chapter 5).

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Chapter 2 • *Machinic*: Machine as Metabolic

One troublesome, central, and often used set of terms spins off from the words *machine* and *mechanical* — principally when they are used in the context of biological organisms. In literatures dealing with biology, synthetic biology, AI, evolutionary algorithms, single-cell and multi-cellular life — machine and mechanical are too generalized for me to ignore and too embedded to edit out. As used by Clark, Le Corbusier, Maturana, Varela, Jonas, Langton, Turing, Venter, and others, machine and mechanical are frequently applied in biology, cognitive science, philosophy, autopoiesis, and architecture. As Guattari suggests: "since allopoeitic machines are always to be found adjacent to autopoietic ones, we should therefore attempt to take into account the *agencements* [assemblages] which make them live together" (Guattari 1995/1993 9). This is a critically good suggestion for situations where descriptions of fabricated machines and programming code collide with biological organisms (Ray 1994). In this collision:

Autopoietic [metabolic, sense-making] machines are autonomous; that is, they subordinate all changes to the maintenance of their own organization, independently of how profoundly they may otherwise be transformed in the process. Other machines, henceforth called allopoeitic machines, have the product of their functioning something different from themselves (as in the car example) (Maturana & Varela 1980 80).

While the various authors cited in this text use the trope of *machine* and *mechanistic* for biological processes — "living systems are essentially mechanistic" (Mingers 1989 161) and "An organism is a machine" (Wilson 1999 99) — that sense is not stable when I propose parallels between bio-hybridized architecture as intelligent and notions of intelligent machines as proposed by Turing (1950. 1951). Biophilosopher Hans Jonas clarifies:

The concept of "machine," adopted for its strict confinement to efficient cause, is still a finalistic concept, even though the final cause is no longer internal to the entity, as a mode of its own operation, but external to it as antecedent design (Jonas 1965 n43).

Canguilhem offers an equally finalistic concept with a more radical biological pedigree:

Machines do not construct other machines, and it could even be said that, in a sense, explaining organs or organisms through mechanical models amounts to explaining the organ by means of itself. At bottom, then, we are dealing with a tautology; for it can be shown . . . that *machines can be considered as organs of the human species* [as extended

phenotypes for example]. A tool or a machine is an organ, and organs are tools or machines. And so it is hard to see how mechanisms can be distinguished from purposiveness (Canguilhem 1992 55 original emphasis).

I loop machine through Jonas's (1965) sense of "efficient cause" to reference metabolic and phenomenological processes via Canguilhem's (1992) machines as "organs of the human" and back to Guattari (1995) for *machines-are-us* and *machines-are-other*. Furthermore, I detect a particular cohabitability of Canguilhem's proposal with Guattari's (1995), "make them live together" when contemplating Clark's (2008a) "cognitive-agent + stick" hypothesis (Chapter 6). From there, I read Guattari's call for organizing *assemblages* as compatible with Maturana and Varela's autopoietic domains. The term I then adapted — *machinic* — is a peace offering to the machine/metabolic dichotomy (Johnston 2008. Raunig 2010) derived from Deleuze and Guattari's (1987 409) *machinic phylum* (definition p56).

More specifically, machinic and machinic phylum accommodates new systems of metabolic containment intended to archive generative architecture's hybridization of biologically synthesized and/or computationally intelligent agents. Machinic phyla, taxonomic groupings morphologically having the same body plan or class of organization, includes neuromorphic (Merolla *et al.* 2014) and living chips (Adamatzky 2013), biorobotic "energy autonomy" (Montebelli 2013), evolutionary electronics (Floreano & Mattiussi 2008. Markoff 2014), and algorithmic learning (D'Andrea 2013). The machinic phylum here importantly takes in metabolic and biointelligent, technological architecture. In this categorical grouping machinic amalgamates theory nested in these pages when confronted with biological-to-mechanical or biological-to-matter hybrids, interfaces, materials, and infrastructures.

Using the word machine to denote both tool and the mechanical within biology — machine as a cell, organ, or body and mechanical as the action of tools — is overwhelmingly confusing. The confusion is compounded when the terms are applied to computation, AI, ALife, and to generative architecture. When I consider smartphones as intelligent agents in the context of Turing's (1950. 1951) thinking machines, or when I draw upon Andrew Wells's (2004. 2006) hypothesis for universal *environmental* machines I hope to avoid further confusion.

Left unaddressed and under articulated, machine as a noun and mechanical as an adjective are inadequate to simultaneously tackle inanimate devices and biological life. To deal with this state of ambiguity, Manuel De Landa rephrased Deleuze and Guattari's machinic explanation as an:

... abstract reservoir of machinelike solutions, common to physical systems diverse as clouds, flames, rivers and even the phylogenetic lineages of living creatures ... called the "machinic phylum" [by Deleuze and Guattari] — a term that would indicate how nonlinear flows of matter and energy spontaneously generate machinelike assemblages (De Landa 1992 135-136).

Machine, mechanical, and machinelike commonly refer to devices, engines, apparatuses, automata, gadgets, and contraptions in traditionally defined contexts. But Maturana, Varela, Clark, and Turing frequently use machine, mechanical, and machinelike to describe biological functions or associations; for example, when Clark cites "machinery of mind" (2008b loc 333). Machinic, by contrast, refers to hybrid lineages where mechanical production enters into partnership with biological, phenomenological, and cognitive systems (Canguilhem 1992).

Machinic, for this thesis, buffers biological systems interfacing otherwise inanimate systems or processes; or, alternatively, when biological functions benefit industrial production; for example, in the discussion of a metabolizing architecture. Machinic also applies where mechanical and biological systems are unified by metabolic or cognitive extension; for instance, the use of a smartphone as a conduit of perception is temporarily machinic when engaged by a student as an extension of sensing or recognition.

Mine is then not a direct reading of Deleuze and Guattari's (1987) machinic. I specify wider biological extension and attributes provisioned by autopoiesis and extended cognition; nevertheless, it aligns with the spirit of reading across boundaries as implied in Deleuze and Guattari's terms — *strata*, *layers*, *rhizomes*, and *assemblages*:

A machinic assemblage is an *interstratum* insofar as it regulates the relations between strata, as well as the relations between contents and expressions on each stratum (Deleuze & Guattari 1987 73 original emphasis).

Sorting and finding commonalities in autopoiesis and extended cognition, Adrian Parr's *Deleuze Dictionary* situates the machinic at the point where human actions conjoin with inanimate objects. Discussing the physical assemblage of *A Thousand Plateaus* (Deleuze & Guattari 1987) as a book, object, and device, Parr comments:

... an assemblage of the book ... and a reader ... is a "machinic assemblage" of actions, passions, and bodies reacting to one another (paper, print, binding, words, feeling, and the turning of pages) (Parr 2010 128).

This consideration emphasizes a logical bond between a cognitive-state object (book in this case), a reader/agent, and phenomenology of memory and recall, a state students may experience with their smartphones as well as with their chosen research sites or objects. Deleuze and Guattari's "relations between contents and expression" (1987 81) and Parr's "bodies reacting to one another" (2010 128) position the machinic as an interface of biologically extended performance (expression, note-taking, or page turning for example) with meaningful things in an object-filled environment — for example, Clark's (2008a) "cognitive-agent + stick" (Bolens 2012. Hayles 2012). Recall Paul Valéry recursively situating Le Corbusier's *Toward an Architecture* (*Vers une architecture*) as machinic by calling the book: "a perfect machine for reading" (Le Corbusier 2007 40).

Extending the machinic, John Johnston's *The Allure of Machinic Life* discusses non-linear reach extending "the cybernetic perspective to what I call machinic philosophy evident in Deleuze and Guattari's concept of assemblage and its intersections with nonlinear dynamical (i.e., 'chaos') theory" (Johnston 2008 xi). I cite, but do not elaborate Deleuze and Guattari's (1987) theoretical affinities with Maturana and Varela's (1980) philosophy except to note:

Guattari proposed to extend Francisco Varela's biological notion of autopoiesis, which referred to organisms that engender their own operations and specific limits, to social systems, technical machines, and all evolving entities once these elements were initially caught in specific arrangements and in becoming (Dosse 2010 394).

While Deleuze and Guattari (1987) often use plant metaphors (i.e., trees, arboreal, rhizomes), I avoid the polemical nature of their framework and its viral terminology as over-determined narrative by *mostly* stepping back from their vocabulary, after commandeering machinic and reclassifying it as autopoietic (De Landa 1992. Deleuze & Guattari 1987. Hayles 2012. Raunig 2010).

Nevertheless, Deleuze and Guattari are formidable theoreticians whose thought permeates critical debate. With that in mind, I look to one aspect of Gerald Raunig's remix of Deleuze and Guattari's philosophy to complete my reading of machinic (Deleuze & Guattari 1987. Di Paolo 2005. Maturana & Varela 1980. Weber & Varela 2002).

As Maturana and Varela stated:

... an autopoietic machine is a unitary system in the space of the components that it produces and which generate the network through their interactions. The autopoietic

network of processes, then, differentiates autopoietic machines from any other kind of unit (Maturana & Varela 1980 79).

From Raunig I hear a plausible theoretical ancestry for the large role machinic henceforth plays as an interface and *interstratum* helping to delineate life, matter, organism, cognition, intelligence, and sometimes phenomena. Below, explaining how Deleuze and Guattari shifted machine into machinic, Raunig writes:

Deleuze and Guattari hence shift the perspective from the question of the form in which the machine follows simpler tools, how humans and tool become mechanized, to the question of which social machines make the occurrence of specific technical, affective, cognitive, semiotic machines and their concatenations possible and necessary (Raunig 2010 30).

Deleuze and Guattari stated directly:

A single [machinic] assemblage can borrow from different strata . . . with a certain amount of disorder . . . the machinic assemblage is [a] metastratum . . . Machinic assemblages are simultaneously located at the intersection of the contents and expression on each stratum (Deleuze & Guattari 1987 73).

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2.1 • Le Corbusier's House vs. Turing's Machine

In the narrative of Modern architecture, Le Corbusier's "A house is a machine for living in" still resonates: a revered pronouncement or a postmodern shriek (Le Corbusier 2007. Wolfe 2009). The maxim and its drawn and built embodiments illustrate a manifestolike communication of design becoming a mantra or icon (Blackmore 1999). I observe this emblematic cultural process through Kirsh's words: "knowledge, capacity, style, and mode of material engagement . . . [are] encoded and transmitted in its artifacts" (Kirsh 2010 121). Those artifacts include Le Corbusier's words, books, paintings, and buildings that transmit: "units of knowledge [that] are primarily concrete, embodied, incorporated, and lived" (Varela 1992 320) even as they migrate from narrative and media to three-dimensional architectural space (Malafouris & Renfrew 2010). This line of thought could be extended between his formal early design vocabulary embodied in pilotis, hovering volumes, ramps, and breezeways and their transformation and abstraction in his later organic shape conversions (MoMA 2013).

Loved or hated, "A house is a machine for living in" may be mined for more radical inspiration or extension useful to biosynthetic projections involving metabolizing architectural intelligence. Literally interpreted, it could join Maturana and Varela's:

... if our characterization of living systems is adequate it is apparent that [living machines] could be made at will (Maturana & Varela 1980 114).

Le Corbusier's mantra may be further sequenced in autopoietic-extended design terms and calculated vis-à-vis Turing's (1950) "Can machines think?" Deconstructed, Le Corbusier's aphorism is a metaphorical catalyst binding a conceptual slogan into a narrative domain where it engages selection and adaptation evolving machinic thinking. Le Corbusier's dictum is thus a powerful algorithm and a generative catalyst that I exploit in a dialectic surrounding biodigital generative design. The dictum's call to design revolution will not quietly wither because its ambiguity may be read in differing living, evolving contexts.

For autopoietic-extended design, exposing "A house is a machine for living in" to Alan Turing's morphogenetic research (Chapter 5) overlaps intelligent machines/organisms in the machinic phylum of Modern architecture (Le Corbusier 2007. Turing 1950. Wells 2004). The stripped syllogism: *nature = machine: machine = architecture: architecture = nature* (p24) then exists to bring about hybridization revealing a long trajectory of machine-to-architecture and intelligence-to-machine crossbreeding (Canguilhem 1992). Along that developmental trail, ideas from Le Corbusier, Maturana, Varela, Clark, Sullivan, and Turing engender possible metabolic systems when the question: Can buildings think? is speculatively answered in the affirmative. (Clark 2008a. 2005. Di Paolo 2005. Le Corbusier 2007. Maturana & Varela 1980. Sullivan 1999. Weber & Varela 2002).

Le Corbusier's oeuvre resonates with twentieth-century mechanical assumptions, judgments, and aesthetics that for decades sustained or tormented professional architecture. His work remains a jumping-off point for an industrial-technological aesthetic and social design continuum recently documented in "Le Corbusier: An Atlas of Modern Landscapes" organized by the Museum of Modern Art in New York (MoMA 2013). In a narrative sense, "A house is a machine for living in" is almost a century-old adage surviving by evolving new meaning reliant on readers' understanding (construction) of living technology and metabolic architecture (Armstrong 2013. Markoff 2014. Spiller 2009).

Accordingly, "A house is a machine for living in" — first loved as a maxim, and then vilified as a cliché — has resurgent significance in an age of biosynthetic materials. Taking Maturana and Varela's stance that living systems could be "made at will" (1980 114) and

reinforcing it with Chris Gosden's (2010) view of a house as an "intelligent object," the slow integration of living attributes and biomimetic properties arrives at architecture's back door. Through that portal I attempt a union where the crisis of environmental sustainability and the performance of buildings come to terms with AI, ALife, synthetic biology, and living technology. By coming to terms with metabolic functions as generative for building performance — bioalgorithmic, biorobotic, biomimetic, and synthetic remedial guidance — sets tactical research categories for learning as a continuation of Le Corbusier's aphorism (Church & Regis 2012. Dawkins 1988. Floreano & Mattiussi 2008. Langton 1988. 1996).

Le Corbusier's words and works (Le Corbusier 2007. MoMA 2013) reverberate in a distinctly different cultural milieu from the one in which Postmodernism (Wolfe 2009/1981) discredited them. In our climate of technological saturation, with algorithmic intelligence, synthetic biology, smart materials, and living technology, "the house is a machine for living in" sounds like a useful public announcement readying us for the *house's* metabolic journey toward intelligent enhancements (Armstrong 2009. Bedau *et al.* 2010. Chu 2004. Lynn 1999. Spiller & Armstrong 2011. Weinstock 2006a b).

I trace one variant of the publically perceived failed Modernist project through the dystopic television commercial "1984" that Ridley Scott (2007) directed for Apple's introduction of the Macintosh computer (Wikipedia 2013c). I do so because the "1984" advertisement is a clear example of media and technology in socio-evolutionary play with relevance to smartphones, social media, and communication. "1984's" phylum-of-spectacle, technology, video, and sound stretches history between George Orwell's *1984* and Scott's own *Blade Runner* (1982) docking it today in the Internet's media ubiquity as a continuous event. Twenty-five years after the broadcast, Scott's "1984" commercial is a YouTube staple (Scott 2004). Ironically, as a historic marker, it still looks contemporary when played on Macintosh-decedent smartphones and tablets, but it does so in a mobile and social media context mirroring the world of big brother surveillance and data mining the advertisement's content protested.

Le Corbusier's aphorism, heroic or fetishized, assumed that humans occupied and embraced constructions — machines — epitomized stylistically by industrial aesthetics found in ocean liners, zeppelins, airplanes, automobiles, streamlined trains, and grain silos (Le Corbusier 2007 99-106). Such stylistic constructions, in urban-scale embodiments — for example, the ocean liner as a floating city or the grain silo as plastic structural masses — came into play for much of the twentieth century conceptually isolated from nature as the International Style, Streamline Modern, or Deco.

In light of "1984" and *Blade Runner* — if less sinister — a machinic variant of Modern aesthetics usefully illustrates a vein of extended cognition through two Cubist oil paintings. For

the moment, these machinic painting help clarify the way extended cognition communicates in an architectural learning system. Le Corbusier himself took part in Cubist experimentation, exhibiting and signing paintings as Charles-Édouard Jeanneret (MoMA 2013). Yet, more precisely related to biological and machinic Modernist roots than Le Corbusier's paintings, Juan Gris and Gerald Murphy's canvases routed machine aesthetics through images of nature, culture, or biology (Brown 1996. Rubin 1974).

In Murphy's 1929 *Wasp and Pear*, the insect and fruit are depicted in a Cubist idiom that I read botanically, anatomically, and morphologically as machinic. The painting ontologically establishes a biologically informed graphic transmitter searching for receptive viewers (Murphy 1929). Parallel to that reading of *Wasp and Pear*, I discuss Duncan Brown's (1994. 1996) Cubist-inspired generative architecture. I therefore make a brief diversion into the autopoietic/allopoietic working of paintings in order to set them as examples of extended cognition structurally coupled (Maturana & Varela 1980) with artistic, communicative objects.

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2.2 • Breakfast with Wasp and Pear

Decades after painting, *Wasp and Pear's* (Fig 12, p123) Cubist depiction of sectioned and machinic life still transmits biological data illustrating autopoietic requirements of unity, organization, structural coupling, and integration of domains. Those attributes Maturana and Varela (1980) theorized long after the painting's creation. While I am not suggesting that *Wasp and Pear* is living, when I look at it through a filter of autopoietic-extended design, I find an embedded expression of phenomenological data in an inanimate (allopoietic) composition pictorially coded by Murphy for communication with viewers (Luhmann 2000). Effectually *Wasp and Pear* performs the function of a cognitive-state object and thereby participates with agency in important aspects of extended cognition (Clark 2008a. 2013). In parallel, for Duncan Brown, the Cubist painting *Breakfast* by Juan Gris performed similarly as a cognitive-state object facilitating the creation of *ZenLux* (Fig 13, p124), his generative system and its coded architectural procedurals (Brown 1994. 1996).

Viewed as cognitive-state objects unpacked via autopoiesis and extended cognition theories, the paintings participate in generative communication (data transmission and idea making) directed to output vivified by a viewer's attendant, attentive perception. Part of the paintings' machinic includes aesthetics whose style and fashion are to be considered code and rules. Luhmann contends that:

... style functions as the level of contact between the system of art and its social



Fig 12. *Wasp and Pear*. 1927. Oil on canvas, 3603/4 x 28 5/8".
Gift of Archibald MacLeish. (1130.1964)
Digital Image © The Museum of Modern Art/Licensed by SCALA / Art Resource, NY.

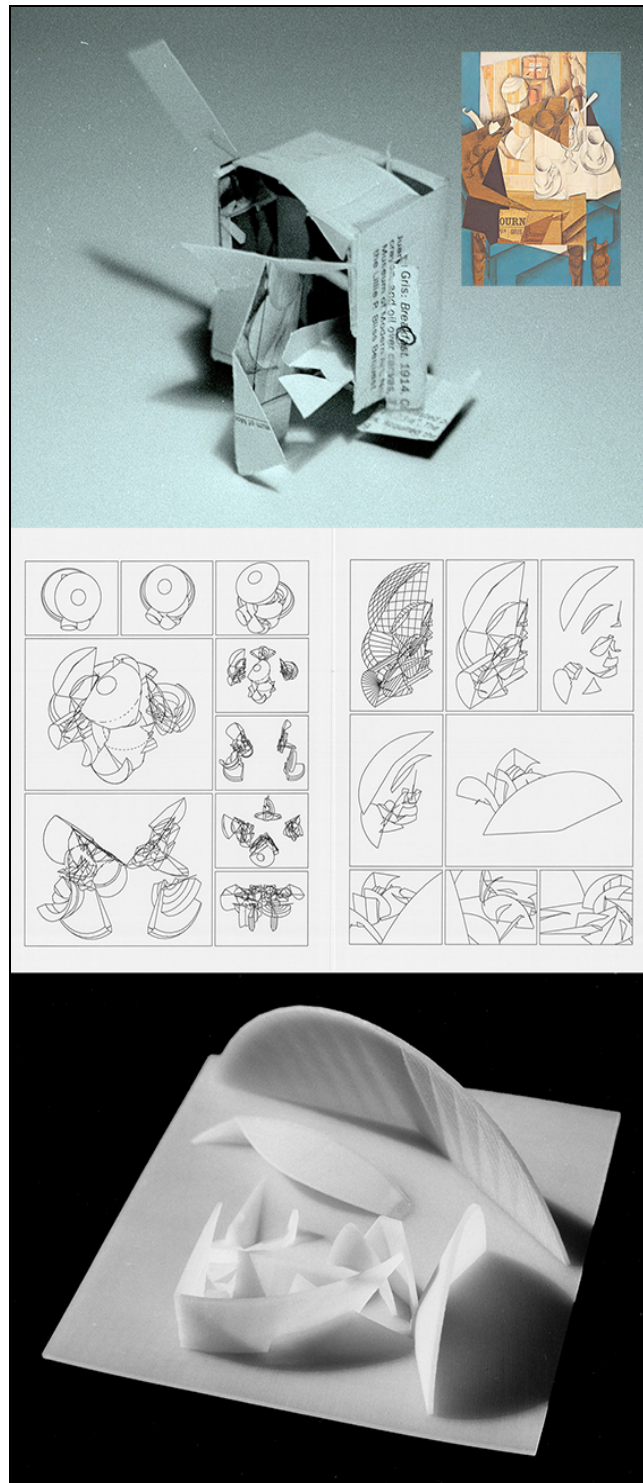


Fig 13. Duncan Brown. *ZenLux*. 1996-present. Top: Folded postcard of *Breakfast* by Juan Gris, 1914 (insert) as a 3D paper model for generative form-finding involving algorithmic development of 2D pictorial and image-edge conditions leading to a 3D digital transplantation of the Cubist work to architectural research (middle), and STL modeling (bottom). Courtesy: Duncan Brown. *Breakfast*. 1914. Gouache, oil, and crayon on cut-and-pasted printed-paper on canvas with oil and crayon, 31 7/8 x 23 1/2" (80.9 x 59.7 cm). Acquired through the Lillie P. Bliss Bequest. Digital Image © The Museum of Modern Art/Licensed by SCALA / Art Resource, NY.

environment. . . . [T]he system of art [here the paintings' rules] must define, limit, and defend the closed nature of its reproduction and the autonomy of its choice of structure. . . . The double function of style — on the one hand the ensuring the production of the elements by the elements of the same system and on the other the delimitation of the field in which this occurs — exactly corresponds conceptually to the definitions of an autopoietic system (Luhmann 1990 204-205).

I cite *Wasp and Pear* and *Breakfast* as aesthetic (stylistic) constructs with properties, attributes, and gestures (Bolens 2012) reaching beyond their painters' intentions to disclose rules and codes that society then evolves. William Rubin, former curator of painting at the Museum of Modern Art, New York, informs us of *Wasp and Pear*: "the objects selected as motifs were so persistently contemplated that they became 'abstractions' to Murphy, and in the process of being assimilated to a governing design, ended as 'objects in a world of abstraction'" (Rubin 1974 9). I think Rubin is overstating the case. Murphy's forms are more graphically codified than abstracted, closer to works by Léger than to abstractions by Picasso or Gris; Murphy's rules are generative and deployed to Cubist stylization as a rule-set within Cubism. Therefore, even if Murphy's forms are Cubist in idiom, they are still illustrative within a communicative and narrative frame consistent with traditional biological prints and their transmission of natural history.

As an aesthetic construct *Wasp and Pear* displays properties that exist similarly in architectural research and the observational interpretation of nature. Keeping my reading within the domain of extended cognition, I reference Guillemette Bolens's *The Style of Gestures* (2012) for her analysis of embodiment and extension in a painting by Chardin. I superimpose Bolens's concepts of viewer cognition via her "perceivable data" and "embodied inferences" (2012 3) as compatible with Clark's (2005, 2008a 2013a) extended cognition to instance autopoietic communication between viewers and objects in ways that Luhmann considers:

Communication tolerates and hides at the same time a high degree of discrepancy in what the participants consciously register and work through. The work of art [architecture] unifies their communication. It organizes their participation. It reduces, although this is a highly improbable state of affairs, the arbitrariness of the foreseeable response, it regulates expectations (Luhmann 1990 194).

Gestures are, of course, communication that signals meaning and data; and, while Bolens (2012 3) discusses types of gestures that do not all appear in *Wasp and Pear* or *Breakfast*, her

analyzing of "perceivable data [through which] viewers may use their personal kinesthetic experiences and memory to infer" experiential and material properties applies to both paintings. Bolens (2012 3) articulates data communicated through a painted hand gesture for example, whose "embodied inferences provide a type of information that is fundamental to the understanding" of artistic intention. She situates paintings as objects involving the transmission of embodied gestural memory. In those gestural transmissions I detect performative data or code retrievable from object/environment decryption, effectually communicating through cognitive-state objects. From her study of paintings, I extrapolate gestural transmission as communication that is present and available to architecture — Le Corbusier's architectural movement and circulation is conveyed and recognized by viewers or users in, for example, iconic ramps for determining gestural occupation, movement, and observation while also being available as graphic tropes for drawings and photographs conveying the same gestural messages of spatial flow and geometric composition.

So, where Bolens (2013 3) analyzes gestural hand transmissions in Chardin's *Boy with Top*, I analyze Murphy's idiosyncratic images depicting phenotypic but, gestural (Hansell 2005), experiential natural history. Transmission is then embedded in paint and graphic signs pointing toward Murphy's perception of objects/agents from nature: wasp, wasp stinger, comb, sliced fruit, and pear seed. Murphy *paints* cognitively extendable data — signaling viewer perception and gestural memory to infer or interpret form and content. In depicting visceral, gestural, or experiential data, Murphy's or Gris's visualizations depend on their painting's twentieth-century aesthetic language or, according to Luhmann (1990 197), the "function of style" in which gesture falls within Cubism's mandated fracturing of perspective, time, and space.

Herein, these Cubist works are gesturally encoded by default of their viewer's knowledge/experience when engaged in an autopoietic-extended design relationship where the paintings contribute to the viewers' interpretation of imagery/situations as cognitively generative. For example, the wasp and wasp stinger may graphically and gesturally activate viewer's knowledge of stinging insects. Murphy's communication requires such prior gestural knowledge, held only in agency, to reconstruct nuance when reading the painting. And, Bolens's (2013) analysis, models ways gestural communication phenomenologically connects viewer engagement to demonstrate performative extended cognition.

Brown (1994. 1996) responded to Gris's 1914 work by gesturally folding a postcard reproduction of the painting to create a physical model (Fig 13, p124). He then captured the folds as the painting's gestural matrix, a template of further potential digital folds he generated in Bentley's 3D MicroStation. By codifying the folds as procedural, he gave the painting an algorithmic extension enacted by ongoing digital implementation. This algorithmic deployment

imparted to Brown's design the heritage of coded aesthetics stemming from Gris; but it also situated ZenLux in the heritage of the generative architecture I route through Turing's hand drawings and digital simulations (Chapter 5).

I see Brown's ZenLux as autopoietic because the unity of *Brown + painting + postcard + computer* produced a coded, structurally coupled, generative response, recursively communicating between Brown and Gris's work for the production of new generative forms. The resulting iterations are cognitively, digitally, and algorithmically reproducible and therefore available to eventual metabolic extension and development. Consequently, even if dormant at times, *ZenLux* algorithms may be activated and transported to generate new variations (Brown 1994, 1996). The translation of a *ZenLux* file into an STL file for fabrication is an example of an architectural instantiation of both *ZenLux* and *Breakfast* in ways neither the painting nor postcard alone could manifest.

In this sense, the postcard image was allopoietically reproduced but was not itself reproductive; the postcard lacked Brown's gestural, animate, and enabling vision and code. Accordingly — *Brown + Breakfast + ZenLux + digital environment* form an autopoietic domain demonstrating potentially infinite digital self-production, variation, and adaption as a new system (Brown 1996). If at some point living technology (Bedau *et al.* 2010) is introduced to *ZenLux* (as is seemingly possible), *ZenLux* may evolve toward metabolic existence.

For architecture, *Wasp and Pear*'s stasis is ontological, not gesturally performative in Bolens's (2010) terms. Murphy's content embeds "perceivable data" that is stored or encoded in its material construction to be regenerated and evolved in participatory painting-to-cognition communication with viewers. In contrast, Brown's folded constructions and folding algorithms constitute gestural and performative architectural and algorithmic steps for materializing models, virtual space, and STL fabrications as both regenerative and reproducible. Bolens and Brown engage historic allopoietic paintings seeking data via agent-to-object communication. The paintings attract partners and viewers, metaphorically, like the pear in *Wasp and Pear* needs and finds pollinators in nature. When a viewer (student or designer) engages an artwork to extract meaning, pleasure, or ideas, the requirement of the artwork's pollination is satisfied for autopoiesis (Maturana & Varela 1980 80-81) and autopoietic-extended design.

The embodiments are dual — wasp and pear each derive from biologically autopoietic living systems. Each exists in its own cellular domains until those domains communicate with other organisms or allotropic constructions. The wasp, for example, is sometimes in communication with its comblike structure, the pear with its cellular production of seeds — the wasp produces extended phenotypes, the pear seed reproduces a new generation of trees (Dawkins 1982. Odling-Smee *et al.* 2012. Turner 2000). When engaged by students or viewers,

the paintings participate in the student's autopoietic domains (Maturana & Varela 1980) — and via extended cognition (Clark 2008a), participate in Murphy's or Gris's or Bolens's or Brown's consequent cognitive (generative) extensions. The paintings, then engaged by living agents (viewers) communicate phenomenological data potentially leading to new ideas as witnessed by Bolens's theory and by Brown's generative architectonic system (not unlike parts of Sullivan's system we encounter in Chapter 4).

I'm privileging *Wasp and Pear* and *Breakfast's* representation of embedded objects, systems of geometry, and communication of biological life along with their blend of machinic, materialized forms and visualized intentions as cognitive, phenomenological, and autopoietic unities that are inseparable, yet still extendable. This type of unity is what Maturana and Varela call "topological unity" (1980 93-94). I further reference the paintings through Maturana and Varela's words:

... phenomenological domains are subordinated to the phenomenology of autopoietic domains [the agent's life] because they depend on them for their actual realization (Maturana & Varela 1980 116).

Critically, topological unity is produced and reproducible — as necessitated by autopoiesis — and embedded in the paintings as affordances according to Gibson (1986), and Wells (2002). Nevertheless, the student or viewer engages and enacts and vivifies that unity. In effect, Murphy's and Gris's creations extend their cognitive artistic vision into phenomenological domains capable of affecting other viewers' own cognitive systems. This communication intersection thus creates temporary "agent-world circuits" (Clark 2007b) from Murphy's or Gris's work to viewer or student — two phenomenological systems (Murphy's or Gris's embedded, student's enactive) — participating in one communicative act that requires the extension of cognition available only from a living viewer/agent. In Brown's (1994) example, the painting is cognitively extended into 3D-folding protocols that lead to extrapolation and coding as procedural and gestural sets of new form-finding options/data resulting in Brown's system of generative architecture.

Maturana and Varela (1980 116) describe autopoiesis in the physical world dealing with living phenomenology but they caution, "the phenomenon of knowing cannot be taken as through there were 'facts' or objects out there that we grasp and store in our head" (1987 25). They recognize environmental phenomenology transmits autopoietic communication and the construction of reality (Lettvin *et al.* 1959) in subdomains of nature such as painting or

architecture, here figured as extended phenotypes and communicative processes for generative inspiration:

Autopoietic systems do generate different phenomenological domains by generating unities whose properties are different from the properties of the unities that generate them. . . . regardless of how they were originated (Maturana & Varela 1980 116).

Evan Thompson further pegs phenomenology in a vein useful to autopoietic-extended design and in context here:

One of the central concerns of phenomenology is to uncover what belongs to the subjective experience of a given sort of mental activity, such as perceiving, imagining, or remembering. . . . Phenomenology is thus concerned with the constitutive features of experience (Thompson 2007 268).

As we saw earlier, Clark does much the same with "biological-agent + stick" (Clark 2007a 265), recognizing temporary co-agency in the stick while it is engaged by a biological agent (Chapter 1. 2.0). He also asserts that extended phenotypic expression is temporarily cognitive; for example, in a cricket's burrow (Clark 2005. Dawkins 1982). If those assertions are valid (Chapter 7. 7.5), extension to human subjective and physical constructions — paintings or machines or burrows or buildings — must be accorded parallel status and recognized not only as cognitively extended but also as phenomenological structures constructed as natural acts (Gibson 1986. Jonas 1966. Luhmann 1990a. 2000. Odling-Smee 2013). Clark may concur. In *Supersizing the Mind* (2008a. b), he situates the biological organism as spinning and maintaining:

. . . the webs of additional structure that accomplishes its own cognizing. Just as it is the spider body that spins and maintains the web that then (following Dawkins 1982) constitutes part of its own extended phenotype, so it is the biological human organism that spins, selects, or maintains the webs of cognitive scaffolding that participate in the extended machinery [architecture] of its own thought and reason (Clark 2008a 123).

Recursively looping extended phenotypic expression found in *Wasp and Pear* or *ZenLux* is a strategy for nurturing agent-to-environment communication and education via extended cognition (Clark 2008a. Hansell 2005). This strategy is useful to research because the cognitive-state object is inert, synthetic, or coded — conditions faced by generative architecture at every

turn (on cognitive objects see Gosden: Chapter 6. 6.1). Whereas current considerations of generative architecture look almost exclusively to code, computers, and simulation, I now look to redefine that vision as limited and limiting.

The expanded definition of generative architecture then involves a working unity (*cognition + technology (art) + environment*), first generating ideas and research, and second as the substrate for learning design and experimentation. In this viewport, generative architecture begins for autopoietic-extended design by fomenting ideas long before computer coding begins for design. This is easily recognized in Brown's project (Fig 13, p124), beginning with the folded postcard (the analog algorithm) as the generative precursor to the designed and fabricated suite of digital works (Brown 1996). In this mode of unification and visualization, the cognitive-technological-phenomenological engages with physical environmental constructions and environments to constitute autopoietic and generative unity:

An autopoietic system is defined as a unity by and through its autopoietic organization. This unity is, thus, a topological unity in the space in which the components have existence as entities that may interact and have relations. For living systems such a space is the physical space (Maturana & Varela 1980 93-94).

In autopoietic theory, Le Corbusier's architectural machines colonizing "physical space" would be considered allopoietic — machines that do not engage in self-production — yet, as topological unities they may function relative to "a component of another [autopoietic] system" (Maturana & Varela 1980 110). Gerald Murphy's machinic painting illustrates how *artist + technology + environment* constitute an autopoietic unity when the painting is cognitively engaged by a viewer (Clark 2008a). In a Corbusian sense, the painting is a machine for data transmission — a machine for thinking — not a decorative expression.

Wasp and Pear and *Breakfast* serve as case studies for agent-initiated, cognitive-state objects in a symbiotic unity constructing autopoietic domains when engaging students', designers', or architects' cognition. A similar formulation must now be afforded to induct buildings and cities (Greenberg & Jeronimidis 2013) into a conversation between cognition, nature, and design practice. That conversation may then key the potential of introducing bioremedial metabolic performance into architecture (Dawkins 1982. Gershenson 2013. Jonas 1966. Odling-Smee 1996. Odling-Smee et al. 2013).

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2.3 • Crickets, Mice DNA & the Uncanny

Andy Clark's theory of extended cognition overlaps domains important to design and architecture. For example, his work factors in the biophysical communication of species-constructed architecture — nests, webs, burrows — as they impact the physiology, perception, morphology, survival strategy, knowledge, and cognitive nature of, not only their builders, but also that of viewers (Clark 2005. 2008a. 2010a). Clark's environmental incursions include human or animal transformed nature developed from a variety of genetic agent-to-material-to-object constructions — what Dawkins calls extended phenotypes (Dawkins 1982. Hansell 2005. Turner 2000. Webb 1996. 2009. Weber *et al.* 2013).

Clark's concept of extended cognition interlaces physical and built, organic and synthetic worlds as its agents register reality in species-specific cognition (Clark 2008a. Maturana & Varela 1980. Lettvin *et al.* 1959). Perceptually, his depiction of constructed reality is compatible with that preformed by *Wasp and Pear* as well as with autopoiesis (Maturana & Varela 1980. 1987). Moreover, Clark's discussions of extended cognition and the construction of subjective reality parallels Lettvin, Maturana, McCulloch, and Pitts's experimental research described in "What the Frog's Eye Tells the Frog's Brain" (Lettvin *et al.* 1959). That research, Katherine Hayles (1999 131) called classic and elegant, noting it established perceptual reality as species-specific cognitive constructions (Chapter 3).

Clark, like Lettvin *et al.* (1959), posits an environmentally collaborative reality. Moreover, Clark's version is open to animate/inanimate data exchange, culture, and the construction of extended phenotypes (Dawkins 1982. Hansell 2005. Gibson 1986. Luhmann 1990a. Odling-Smee 1996. Turner 2000). That conceptualization permits autopoietic-extended design to aid cognitive production of subjective reality (Lettvin *et al.* 1959) where experiencing/constructing the reality of a painting, nest, or building results in species-specific cognitive input/output as autopoietic.

To cite one dramatic example with architectural relevance, Clark (2005) connects Scott Turner's (2000) research into the biological "tuned impedance" of two species of cricket burrows (Clark 2008b loc 4875. Turner 2000. Webb 1996). Crickets, *Scapteriscus acletus*, and *Gryllotalpa vinae*, build earthen burrows to function as sonic amplifiers of the males' mating call. Building sonic amplifiers, the crickets develop their burrow architecture with a direct role in their biological processes. The burrows' architecture is then an extended phenotype enhancing species reproduction that impacts biological selection and inheritance (Dawkins 1982. Hansell 2005). Here, to relate genetic architectural expression verified in mice but not yet studied in crickets, I cite evidence. In January 2013, Harvard scientists announced and *Nature* published and editorialized the burrow constructions of field mice, *Peromyscus polionotus*, as genetically

established. The mice burrows are DNA sequenced, genetically extended phenotypes traceable to two individually mapped genes (Goymer 2014. Weber *et al.* 2013).

Cricket songs and burrows are instances of what Clark discusses as cognition-to-environment relationships; if these are genetic, a more embedded view of built constructions as part of nature enters consideration. Clark's narrative includes conscious or unconscious relationships between a living species, inert matter, technology and their resultant structures in a wild or urban environment — earth construction for the cricket, and as we shall see later, flight performance from a seedpod (Fig 29, p278). The narrative of crickets, seedpods, and paintings, looked at as specie-specific transformations of materials and phenomenological data into physical constructions, is thus germane to architecture contemplated through metabolic-to-mechanical hybridization.

The spectrum of nature that Clark surveys is not limited to the soft, wet, or hard — just as his view of cognition, although cranium-bound, is not cranium-limited. If he persuasively illustrates a species as biologically and environmentally interlocked — crickets and their architecture, for example — then, by extrapolation, humans may be equally biologically and environmentally interlocked (Dawkins 1982. Hansell 2005. Turner 2000). We build, design, paint, write, and construct worlds to enhance our individual and group reach. Ultimately, our activities are selection/adaptation survival tactics, extending cognition to participate in nature (Di Paolo 2005. Maturana & Varela 1980. Weber & Varela 2002) and to technologically and ecologically tune our environments (Coyne 2010. Dawkins 1982).

Allopoietic machinics, such as a cricket's burrow or *Wasp and Pear*, do not by themselves constitute life forms. They are rather, members of a category of animal production that, for example, allows us to credit a hut, tool, automobile, or smartphone as (sometimes) interactive with cognition (Maturana & Varela 1980 79-81). Autopoietic systems, by definition, must be generative, recursive, and self-producing (Maturana & Varela 1980). While some living properties may now be found in AI and synthetic biologies and are seemingly drifting toward the fabrication of industrial products such as smartphones, it is unclear how near-metabolizing and *nearly* intelligent materials will impact design and architecture (Adamatzky 2013. Bedau *et al.* 2010. 2013. Gershenson 2013). Rachel Armstrong, considering a systems-theory approach (von Bertalanffy 1969. von Foerster 1990. Luhmann 1990a. Schumacher 2011) articulates a future vision for architecture.

Using the systems [autopoietic] architecture model, which can be seen as similar to systems architecture in computer science (CS), the built environment (or the system in CS) becomes integrated with the natural world (the hardware) and a series of networks

or functions that are orchestrated through organizing hubs of activity and computation (the software). . . . Systems architecture anticipates the development of a new set of materials that possess the ability to connect nonliving (traditional) structures with vital structures (e.g., nature or the products of living technologies . . .). The theoretical organizing nature of these materials implies that they are likely to exhibit some of the properties of living matter such as self-organization, responsiveness, growth, or movement, and would essentially constitute a new generation of smart materials. Unlike contemporary smart materials, these speculative organizing systems would possess embodied complexity, be capable of chemical computation, and not need to rely on traditional computing methods or human intervention to generate their responsiveness (Armstrong 2010).

Armstrong (2010. 2011. 2012) and I agree on a biological evolution for architecture, materials, and computation understood through biology, systems, complexity, and non-linear dynamics. Yet, I move in a different direction in order to organize research and e- and m-learning procedures powered by autopoiesis and extended cognition theory (Clark 2008a. Di Paolo 2005. Maturana & Clark 1980. Weber & Varela 2002). By factoring in complexity and natural dynamics as part of design learning (Fenwick *et al.* 2011. Mason 2008a. b), and supporting the conjunction of technology and biology affecting architectural materialization, I see the necessity for reformulating the pedagogy of generative design and research in order to break the conceptually restrictive barriers of binaries such as natural/artificial, natural/built, and body/environment.

I welcome uncertainty, challenge, and risk in what Bayne (2010) calls "the digital uncanny" as native to learning and part of complexity — beneficial, in fact, to experimentation with metabolic and biodigital design. Pedagogical experimentation may thus generate exploration and discovery that are useful for the development of autopoietic-extended design as a specialized branch of generative architecture (Bayne 2010. Barnett 2007. Fenwick *et al.* 2011). Bayne contextualizes some learning processes with:

. . . the digital uncanny reflects the ontological disturbances opened up by a genuine higher education. . . . [I]t works with the very idea of the learning process as volatile, disoriented, and invigorating, and it also stretches conventional assessment frameworks to their limits (Bayne 2010 10).

Between allopoietic machines and autopoietic life, questions of an uncanny pedagogy deserve consideration for design learning roles involving AI, ALife, and synthetic biology (Bayne 2008. 2010). But, when AI and ALife (Bedau 2003) are used to repurpose questions of how such systems might be analyzed in relation to their merger with biological functions and living technologies for architecture (Armstrong 2012), the questions drive research along with learning. For example, following Montebelli *et al.* (2013) we might ask which areas of "biological detail should we impose on biomimetic modeling [in building sensing, monitoring, control, performance] in order to achieve useful cognitive properties that characterize living systems?"

The associated goals of generative architecture and design learning, teaching, mobility, and research might be remixed in designs and models fitted between current e-learning, experimental practices, and biotechnology evolved for instance by crowd-sourcing scientific research (e.g. experiment.com) seen in currently emerging web-based research sites using videogame strategies such as Foldit (2008) and OpenWorm (2013). For OpenWorm, the digital simulation, including a CAD designed body and organs, illustrates one form/forum a research oriented metabolic generative architecture might emulate for open collaboration, multi-authored programming, and e- and m-learning research.

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Chapter 3 • Frog Vision & Different Realities: Constructing Autopoiesis

“What the Frog’s Eye Tells the Frog’s Brain” (Lettvin *et al.* 1959) established biological evidence that perception/cognition determines reality. It documented that species visualize/cognize differently, thus registering different realities (Hayles 1999). Subsequently, these findings were reinforced with experiments showing that different animals register reality in color systems inconsistent with each other and with human perception (Varela *et al.* 1993). Maturana recalls:

When Jerry Y. Lettvin and I wrote our several articles on frog vision . . . we did it with the implicit assumption that we were handling a clearly defined cognitive situation: there was an objective (absolute) reality, external to the animal and independent of it (not determined by it), which could perceive (cognize), and the animal could use the information obtained in its perception to compute a behavior adequate to the perceived situation (Maturana & Varela 1980 xiv).

Hayles explains that Lettvin and Maturana’s work supported empirical deductions that cast long-established concepts of objective reality into doubt. “Maturana and his coauthors demonstrated that the frog’s sensory receptors speak to the brain in a language highly processed and species-specific” (Hayles 1999 134). When such implications of research are traced, they assist in rewriting our understanding of perceptual and cognitive mechanisms, as well as countering the notion, that all species share a fixed reality. In Hayles’s words:

Maturana concluded that perception is not fundamentally representational. He argued that to speak of an objectively existing world is misleading, for the very idea of a world implies a realm that preexists its construction by an observer. Certainly there is something “out there,” which for lack of a better term we call “reality.” But it comes into existence for us, and for all living creatures, only through interactive processes determined solely by the organism’s own organization (Hayles 1999 136).

Associatively, and while discussing the autopoietic construction of reality, I introduce two constructivist layers that impact design research. The first from Luhmann is important to autopoiesis and its impact on cybernetics, philosophy, and psychology (Clark 2008a. Hayles 1999). As with Maturana’s demonstration of divergent realities, Luhmann’s assertion posits data and information as sensory and perceptually constructed:

Information, utterance, and understanding are aspects that for the [autopoietic] system cannot exist independently of the system. Even "information" is not something that the system takes in from the environment. Information doesn't exist "out there," waiting to be picked up by the system. As selection it is produced by the system itself (Luhmann 1990 3-4).

To phase-in knowledge "produced by the system" while acknowledging systems theory with its direct associations with autopoiesis (Luhmann 1990a), Brent Davis writes:

Knowledge-producing systems . . . are among the phenomena that are studied by those interested in systems theory, one of the major tributaries to complexity thinking. Systems theorists focus in large part on living systems, [autopoiesis] seeking to understand the manners in which physical systems self-organize and evolve. These systems include brains, individuals, social collectives, and cultures (Davis 2008 52).

Autopoiesis then appears deployed to illuminate metabolic complexity in living and social systems as symbiotic with environments and objects, even if it lacks mechanisms to simultaneously network data through them (Maturana & Varela 1980). But, this lack in autopoiesis is compensated for in autopoietic-extended design partnership with extended cognition and its construction of sense-making and environmental networking (Clark 2008a. Di Paolo 2010. Menary 2010. Thompson 2007. Weber & Varela 2002). While autopoiesis may not allow for data sharing outside of discrete domain constructions, its hybridization with extended cognition does (Clark 2003. 2005. 2007a. b. 2008a. b. 2010). Herein, cross-boundary sharing enables E.O. Wilson's important digital (and distinctly Turingesque) reading of complexity theory "as the search for algorithms used in nature that display common features across many levels of organization" (Wilson 1999 95).

Autopoiesis and extended cognition conjoined initiate new visualizing and biomimetic potential for reconfiguring design pedagogy and research. Moreover, curated technological mediation through smartphones/apps repurposes the devices for design research that reinforces systems of perception with physical/virtual data. It is then my contention that emerging technologies, living technology, computational simulation, and digital fabrication — app accessed — enhance and expand design learning at fundamental levels (Dutton 2013. McGonigal 2011. Pew Internet 2006).

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3.1 • Frog, Cricket, Bacteria, Cognition: Autopoiesis & Architecture

To organize biological requisites for living systems, *Autopoiesis and Cognition* asks, "What is the organization of the living?" and "What takes place in the phenomenon of perception?" (Maturana & Varela 1980 xii). I extend these questions to generative architecture and learning in the context of visualization and project development, but also to Turing's (1950) inquiry: "Can machines think?" The troika below then provides entry points for considering whether architecture can, or should, be associated with autopoietic metabolic performance:

- 1) "What is the organization of the living?"
- 2) "What takes place in the phenomenon of perception?"
- 3) "Can machines think?"

Tracking from the questions, autopoietic-extended design helps to investigate and formulate how natural properties or attributes may suit the functionality of buildings and how those properties may be observed and visualized by students. The questions highlight processes important to architectural learning, pedagogical programming, and generation of ideas before they apply to generative design procedures in coding, computation, and fabrication.

In "On Machines" Guattari (1995 8) quotes Pierre Lévy discussing processes such as "trying to break down the ontological iron curtain between being and things." If the iron curtain between nature, technology, and being is similarly broken down, bioremediation may be considered as viable through metabolic intelligent performance of architecture. From there, natural attributes could be formalized, discussed, and taught as infrastructural systems; for instance, phototropic leaf folding and shape-shifting to inspire facade control (Focatiis & Guest 2002) paired with photosynthesis prototyped in the artificial leaf developed by Daniel Nocera (Hitt 2014). Leaf folding and photosynthesis as models for biomimetic building performance in aerodynamic and energy functions (Figs 9-10, pp87-88) might further look to microbial fuel cells (MFCs) as discussed by Montebelli *et al.* (2013) where robotic functions are conceived as "biomechatronic symbiont[s]" in the life cycle of metabolic structures.

"Grasping the chaotic" is how Guattari (1995 10) describes: "a momentary grasp of complexity that is inhabited by all kinds of potentialities." In this frame, student research is given a theoretical metaphor advocating holding onto, even nurturing complexity that could subsequently unfold into hybridizing materials and morphologies for testing in physical or computational models. "Grasping the chaotic" is then a challenge to learn from "the chaotic." And, Guattari's voice is consistent with risky and uncanny pedagogy discussed for autopoietic-

extended design (Barnett 2007. Bayne 2008. 2010. Davis 2008. Fenwick *et al.* 2011. Mason 2008a. b).

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A preface, an introduction, two asynchronous essays, and the hint of discord between authors constitute: *Autopoiesis and Cognition: The Realization of the Living*. The book reads more like a thematic collection than a sustained, argument, yet its impact has been seismic (Maturana & Varela 1980). The volume's earliest essay, "Biology of Cognition," was authored by Humberto Maturana in 1970; the text-of-record, "Autopoiesis: The Organization of the Living," was coauthored by Maturana and Francisco Varela in 1973. Maturana was the sole author of the introduction (Maturana & Varela 1980). In subsequent years much of the book has been appropriated or rebranded as "enactive," "embodied," "extended," and here, "generative" (Di Paolo 2005. Hayles 1999. Mingers 1995. Thompson 2007. Varela *et al.* 1993. Weber & Varela 2002).

The span of ten years separating *Autopoiesis and Cognition's* introduction from its first essay, and the seven years from the second, provided a reflective opportunity for Maturana to reevaluate both essay's structural demands and component organization (Maturana & Varela 1980 xxvii-xxx). In those years, Maturana more fully explained his vision of autopoietic social systems, creativity, and ethics, thereby extending the original essay's scope (Maturana 2002. Zeleny 1981). Varela took a different (but still related) tack and sent autopoiesis in directions of enactive systems (Varela 1992. 1997. Varela *et al.* 1993. Weber & Varela 2002. Zeleny 1981).

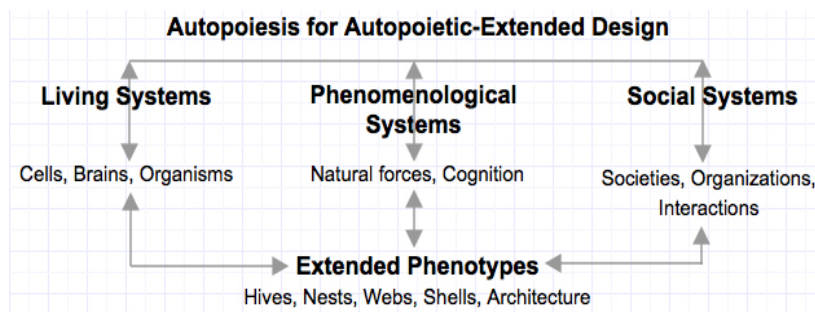
So, while organizationally disorienting, with the quality of language: "cumbersome — many would not hesitate to call it tortured —" (Hayles 1999 136) *Autopoiesis and Cognition* nevertheless delivers theoretical impact valuable for distinguishing animate and inanimate systems crucial to autopoietic-extended design. The volume's theoretical logic and biological organization almost immediately attracted scholarly comment, discussion, and revisions that brought autopoiesis to the attention of cyberneticists, social critics, philosophers, and scientists (Clarke & Hansen 2009. Di Paolo 2005. Hayles 1999. Luhmann 1990. 1990a. Maturana & Varela 1987. Varela 1979. Thompson 2007. Weber & Varela 2002). Those scholars and others then defined amendments from which I graft a retooled autopoiesis to extended cognition (Clark 2008a).

Furthermore, the history of autopoietic amendments, corrections, and redeployments testifies to the text's dialectic adaptability in research involving complexity and self-organizing systems (Di Paolo 2010. Luhmann 1990a. Thompson 2007. Wheeler 2010). And, it is through this dialectical pedigree that autopoiesis is positioned as adaptive for the theoretically complex

job of investigating metabolic systems and intelligence for very big machines — architecture (Bedau *et al.* 2010. Luhmann 1990a. 2000. Mingers 1998. Schumacher 2011).

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Autopoiesis and Cognition's Introduction suggests potential for systems theoretically capable of integrating designer, technology, and environments as autopoietic unities when the agent — designer, student, or researcher — is the metabolic engine confronting the environment (Maturana & Varela 1980). In this configuration "a living cell, a multicellular animal, an ant colony, or a human being behaves as a coherent, self-determining unity in its interactions with its environment" (Thompson 2007 37). I chart the integration of autopoietic systems based on, and expanded from, Luhmann (1990 2) like this:



Searching for attributes and properties of living systems is part of autopoietic-extended design's protocol for identifying metabolic, cognitive, and synthetic relationships appropriate to, and available for, student experimentation. The search sets ocular and technological observation, direct experience, and interpretation of data as frontline (pre-computational) aspects of generative architecture (Clark 2008a. 2005. Di Paolo 2005. Thompson 2007. Weber & Varela 2002). The method involves cognitive prediction (Clark 2013a. Maturana & Varela 1980), search, and identifying (autopoietic) living sources as causal mechanisms in nature to first inform conceptual design and then performance of buildings. Therefore, at fundamental levels, the translation from nature to architecture involves parallels with animal-built shelters and typologies of extended phenotypes (Chapter 7. 7.4) informing new metabolic architectural prototypes (Hansell 2005. Montebelli *et al.* 2013. Ray 1994. Turner 2000. Weber *et al.* 2013).

To define life- and matter-detecting intelligence — sense-making abilities — I turn to Weber and Varela (2002) and Di Paolo (2005) for a working description of intelligence. From Di Paolo's minimalist classification below, I consider how systems of intelligence may begin: "the normative engagement of a system with its world" (Di Paolo 2008 12), and contend minimal systems of sense-making/intelligence should be explored for architectural performance. I later expand upon sense-making and low-level cognition in buildings by determining methods for

experimenting with learning and research that considers bioremediation as an architectural attribute related to Di Paolo's characterization of cognition:

Cognition is an embodied engagement in which the world is brought forth by the coherent activity of a cognizer in its environment. Even in the simple organisms, this engagement involves the structuring of the immediate milieu with the consequent building of regularities which feedback into the organism itself (Di Paolo 2008 12).

What Di Paolo suggests in the world "brought forth," is an example of immanence and the construction of reality that dovetails with other thinkers' views of autopoietic and phenomenological functions (Jonas 1996. Lettvin *et al.* 1959. Luhmann 1990a. Thompson 2007. Zeleny 1981). Cognitive and sentient constructions of reality yes, but not as conventionally defined by comparisons with higher animals. I'm not equating high-level perceptual systems with intelligence only equivalent to humans. De Paolo's definition, directed to metabolizing agents, does not exclude single cell organisms, insects, machines, or machinic architecture — it says: "coherent activity of a cognizer in its environment" (2008 12). Di Paolo leaves possible biological alternatives or hybrid intelligences as contenders. Significantly, his definition is consistent with *The Oxford Companion to Philosophy* where:

... recently, cognition has been conceived as the domain of ... phenomena involved in thinking about the world using ... aspects of sensory perception where this involves representations of a spatial world and the intelligent processing of sensory input (Honderich 2005 145).

Ongoing amendments from biology, mathematics, philosophy, and cognitive science have impacted *Autopoiesis and Cognition's* original requirements for living systems, augmenting and empowering them differently. Maturana and Varela's own *The Tree of Knowledge* (1987) devoted coverage to amoeba and bacteria in the context of cognizing cellular behavior. Elsewhere, Weber and Varela (2002) for example, formulated routes for purposive functionality, and Di Paolo restructured autopoiesis for evolutionary adaptation:

Autopoiesis provides a systemic language for speaking about intrinsic teleology but its original formulations need to be elaborated further in order explain sense-making. This is done by introducing adaptivity, a many-layered property that allows organisms to regulate themselves with respect to their conditions of viability (Di Paolo 2005).

In aggregate and in the context of globalized communication and mobility, autopoiesis may be activated for environmental research where theory, in relation to design epistemology and pedagogy, offers new investigative support (Clark 2008a. Di Paolo 2010. Jonas 1966. Luhmann 1990a. Odling-Smee 1996). Keeping in sight technological systems that merge design processes vis-à-vis biology, computation, synthetic materials, nature, and designer cognition, I argue the need to augment generative bioarchitecture with a generative theoretical methodology capable of hosting metabolic-to-machine experimentation. Part of that methodology includes interconnecting disciplines (science, communications, technology, computation) for research and learning supported by complexity and emergence (Bird 2003. Bragg 2013. Mason 2008a. b). The student may then construct a research base adaptable to strategies of designing and prototyping living and material, intelligent and passive biosystems for building performance (Clark 2003. 2008a. 2010b. Malafouris & Renfrew 2010. Robbins & Aydede 2009. Thompson 2007).

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3.2 • Neuromancer & Rebooting Autopoiesis

Discussing cognitive domains, Maturana — known among the inner circle of first-wave cybernetic theorists (Hayles 1999. Clarke & Hansen 2009), deployed “consensual domains” in his Introduction to *Autopoiesis and Cognition* (Maturana & Varela 1980 xxix). As participatory, consensual domains illustrate and expand concepts of autopoietic situatedness interfacing physical worlds and objects in an environment of animate and inanimate intelligences (Malafouris & Renfrew 2010). Therein, like “consensual hallucination,” William Gibson’s (1984 69) coinage in *Neuromancer*, these cognitive-engaged spaces deploy and integrate phenomenological, natural, and virtual constituents. Yet, unlike Gibson’s virtual reality, autopoietic-extended design’s consensual domains maintain physicality that is itself multispatial, dimensional, and sometimes metabolic for constructing reality (Lettvin *et al.* 1959).

Furthermore, Maturana’s consensual domains include cognizing 3D spaces (Malafouris & Renfrew 2010) where physical participatory data is embedded in objects and organisms (as with extended cognition), but organized and interpreted through metabolic and/or *cybernetic* activity. These domains, in various configurations possible via autopoietic-extended design, establish the agent (student/designer) as originator and developer of design vision in, so to speak, their mind’s eye, as well as within extended cognitive domains that include technological communication and physical design output. This is within bounds of phenomenological *concatenations/perturbations* that Maturana and Varela (1980) acknowledge as autopoietic, and that I bridge for design research to Clark’s (2008a. 2013a) extended cognition.

Consensual domains, as with virtual game space (Chapter 7. 7.2), can be mapped in realms bounded by cognition and technology to encompass physical, environmental spaces in addition to virtual and augmented reality. Twin "space" occupancy — supported by autopoietic-extended design — is then a little explored staging ground for in-field design research that subsequently aids plugging data into biodigital or metabolic design experimentation and machine fabrication. Twinned space consensual domains are therefore conceptual staging grounds for operations in physical/phenomenological and virtual spaces channeled to design research capable of registering sense-making (Di Paolo 2005) while remaining aligned with physical nature.

With Maturana's 1980s participatory domains, the context of phenomenological consensual domains allows the spatial envisioning of a digital autopoietic-extended design practice located in physical, technological, biological, and virtual territories. In this configuration, autopoietic-extended design aids evolving recognition of sensory, perceptual, metabolic, and intelligent realms linked with non-cognitive life systems and natural forces and matter (Brenner *et al.* 2006. Calvo Garzón 2007. Di Paolo 2005. Gagliano *et al.* 2014. Mancuso 2010. Trewavas 2005). Further, when activated between student cognition and environment, autopoietic-extended design promotes affordances and data flows (Gibson 1986) sourced in objects, biological processes, and environments (Clark 2008a. Maturana & Varela 1980). Maturana emphasizes phenomenologically generative vulnerability and creative potential when he states:

... there are certain experiences that cannot be fully specified in a human society without destroying the basic individual structural plasticity needed for the establishment of consensual domains and the generation of language and, hence, for human creativity in general (Maturana & Varela 1980 xxix).

"Experiences that cannot be fully specified" include thoughts/visions embedded in creative design, architecture, and paintings. Thus Maturana testifies to autopoiesis as accommodating "individual structural plasticity" (Maturana & Varela 1980 xxix) or generative creativity. Language, text, drawing, and design are consensual across social disciplines and should be read in the generative states and domains of human-to-nature feedback systems — linguistic, biologic, semiotic, mathematic, constructive, and cybernetic — all interface coded design within the learning scaffold evolving in this thesis (Gibson 1986. Jonas 1966. Odling-Smee 1996).

Maturana's "Biology of Cognition" (Maturana & Varela 1980) follows his Introduction with relationships, descriptions, and propositions that move beyond standard examples of cellular life. In the Introduction he writes: "all kinds of societies are biologically legitimate" (Maturana & Varela 1980 xxix). In "Biology of Cognition" he specifies hierarchical autopoietic relationships between bees as cellular organisms where a cell is itself autopoietic and contained within the living individual, cognitively processing, autopoietic bee (Maturana & Varela 1980 11). But Maturana stops there failing to address the hive as cognitively extended and thus a membranous and phenomenological interface (Hansell 2005). As discussed (Chapters 1. 1.7 & 7. 7.4) in relation to extended phenotypes, I categorize nests, hives, and buildings as architectural-to-environment interfaces citing J. Scott Turner from *The Extended Organism*:

... animal-built structures are properly considered organs of physiology, in principle no different from, and just as much a part of the organism as, the more conventionally defined organs such as kidneys, hearts, lungs, or livers (Turner 2000 2).

In defense of this statement Turner describes how a beehive or termite mound functions biologically as an extended phenotype:

... these mechanisms involve structures built by the colony inhabitants, structures which harness and transform both metabolic energy and physical energy in the environment to power the external physiology that social homeostasis requires (Turner 2000 187).

Yet, Maturana's Introduction also suggests he was reconsidering earlier thoughts as they matured (Paucar-Caceres & Harnden 2011), emphasizing the hospitality autopoiesis offers creativity by pointing out involvement with "works of art," "human aesthetic design," and "ethical choice" (Maturana & Varela 1980 xxviii. Luhmann 2000). In doing so, he expanded autopoietic biological emphasis to include (or not preclude), certain actions of appropriation (reaching out) — extension, infection, evolution, and hacking (perturbations) — that participate in communication and social and environmental interactions (Luhmann 1990. Maturana & Varela 1980. 1987). Varela, independently proposed an ongoing series of enhanced autopoietic pathways (Di Paolo 2005. McMulling & Varela 1997. Varela 1979. 1992. 1996. 1997. Varela *et al.* 1992. Weber & Varela 2002).

Still, there are hurdles and barriers set up by *Autopoiesis and Cognition* involving environmental strictures vis-à-vis metabolic life. Maturana and Varela (1980 81) insisted:

"Autopoietic machines do not have inputs or outputs." They back that statement with: "Living systems, as physical autopoietic machines, are purposeless systems" (1980 86). What Maturana and Varela qualify is not that autopoiesis must be exclusively closed (no communication or input/output of any kind) but that it is *operationally closed* (e.g. bee cells in bee being.)

Maturana & Varela stress: "living systems are machines" (1980 76), yet no machine works without input/output; for example, energy input and work (heat) output. So, while there have been various theoretical strategies for working around the original prohibition on input/output, not until Weber and Varela's (2002) "Life after Kant: Natural Purposes and the Autopoietic Foundations of Biological Individuality" and Di Paolo's "Autopoiesis, Adaptivity, Teleology, Agency" (2005), did theoretical flexibility align to support hybridized partnerships necessary for autopoietic-extended design (See also von Bertalanffy 1969. Zeleny 1981).

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Autopoietic consensual domains (Maturana & Varela 1980 xxix) are plotted as phenomenological and physical manifestations of theoretical and biological spaces (rule-based and sometimes physically occupies sites for student research) hosting individual perception, cognition, and machinics. Agent-activated domains may therein combine cognitive, technological, and virtual sources of data for generating ideas from objects, organisms, materials, systems, and environments (Fig 14, p145). I advocate cultivating such domains as generative spaces for learning where *student + technology + environment* interact as autopoietic units to construct and interpret data. Domain integration then facilitates communication of data reliant on biological, social, technological, and environmental engagement by students in virtual, cognitive, and physical spaces — all compatible with extended cognition (Clark 2001a, 2003. 2007a. 2008a. 2010b).

Remembering the second of Maturana's questions (Maturana & Varela 1980 xii), "What takes place in the phenomenon of perception?" prompts a look at perceptual-insight mechanisms for design such as sense-making, in order to configure autopoiesis with extended cognition. Teleology or purposefulness (Nagel 2012), enacted via sense-making delivers output data — say, in a building facade — that may soon include non-conscious intelligence interpreting and then determining metabolic actions from sensors and/or actuators engaging in architectural performance (Di Paolo 2005. Maturana & Varela 1980 xii. Weber & Varela 2002).

So, whereas Maturana and Varela (1980) addressed the biological perception of reality as differing between species and their domains, Clark theorizes perceptual reality via collaboratively distributed cognition, in an environment whose focal length is that of human perception (Clark 1997. 2003. 2008a. c. d). Thus, where Maturana (Lettvin *et al.* 1959) theorized

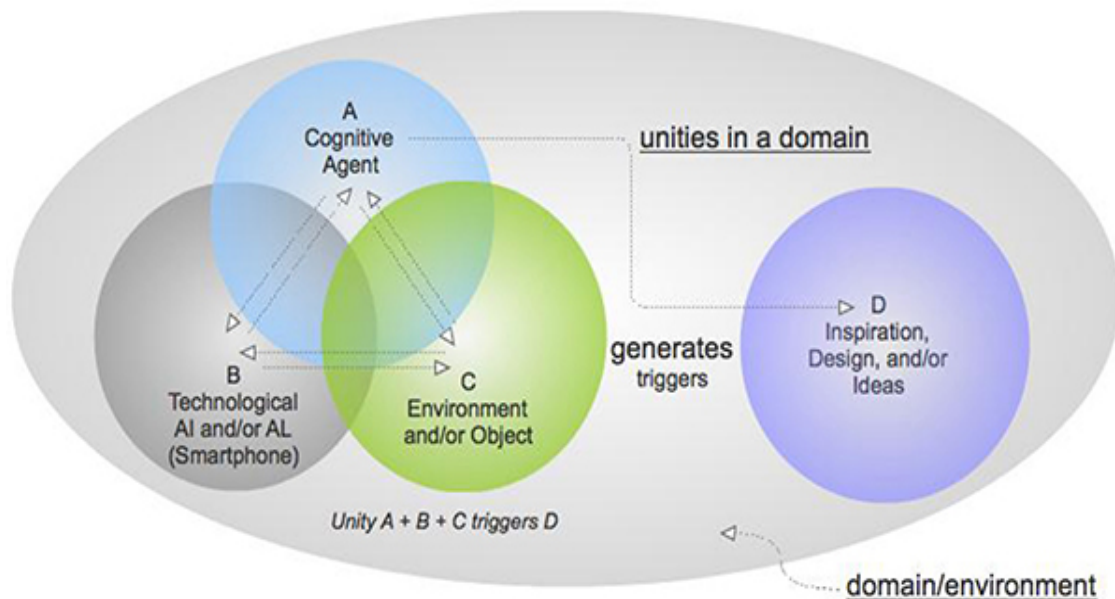


Fig 14. Autopoietic operational unity of *Student + Technology + Environment* within a graphically visualized domain. Drawing: Dennis Dollens.

differing biological systems defining the construction of individual reality, Clark theorizes human cognition dispersed across domains of animate and inanimate matter, critical to the construction of design knowledge. By overlapping perceptions and affinities cognitively distributed in the largest of possible fields — nature — Clark's position is open to autopoiesis as an "interstratum" (Deleuze & Guattari 1987 81) where hybridized autopoietic-extended design regulates and unfolds "relations between strata" (1987 81) for processes of design research integral with biodigital practice (Clark 1997. 2003. 2008a. Gibson 1986).

Maturana (1981. 2002) defended, but also restructured his and Varela's thesis, opening it to additional functions other scholars had already begun (Di Paolo 2005. Luhmann 1990a. Maturana & Varela 1980. Noë 2009. Thompson 2007. Varela 1981. Varela *et al.* 1992. Weber & Varela 2002). By doing so, he acknowledged autopoiesis as an evolutionary, self-organizing theory that I continue to draw upon for the organization of design pedagogy and method. As discussed earlier in this chapter, Maturana's frog research (Lettvin *et al.* 1959) established that cognitively different perception documented that species construct their own reality (Hayles 1999 131). Separately, Varela arrived at a similar conclusion:

Reality is not cast as a given: it is perceiver dependent, not because the perceiver "constructs" it at a whim, but because what counts as a relevant world is inseparable from the structure of the perceiver (Varela 1992 330).

And:

Perception is not simply embedded in and constrained, by the surrounding world; it also contributes to the enactment of this surrounding world. Thus, as Merleau-Ponty notes, the organism both initiates and is shaped by the environment: he clearly recognized that we must see the organism and environment as bound together in reciprocal specification and selection (Varela 1992 331).

Lettvin *et al.* (1959) empirically established that reality is constituted by individual species; documenting that no single phenomenological reality exists (Hayles 1999). When species perceive objects and track them in space, autopoietic conditions apply; but what is perceived, as stable reality is not equivalent between species, and thus renders the resulting cognition, relative. As we find later, Weber and Varela's (2002) and Di Paolo's (2005) work appends autopoiesis with adaptation and sense-making evolved from thinkers such as Jonas (1966), Gibson (1987/1979), Odling-Smee (1996), Luhmann (1990a), and Zeleny (1981) bringing their views on the environment and social systems into a frame of autopoietic reality.

For design learning and research, technologically channeled data emerges through autopoietic-extended design as cross-species and virtual/physical representative (environment-to-human perception), calling to be understood via Lettvin *et al.* (1959) in order to be translated — data-to-information — for architectural performance. Herein lies a double signal: what is documented in observational research must be stable and scalable to account for performance in material design systems. As a precursor to metabolic-generative and biodigital architecture, that recursive information (Hayles 1999) here takes into account Turing's universal machine and biological simulations (Turing 1936. 1952) and then loops forward to algorithmic intelligence, computer animation/graphics, and generative design systems (Lindenmayer 1968. Prusinkiewicz 1994. Veen & Lindenmayer 1977). In this feedback/feedforth context, Katherine Hayles writes:

It all started with a Frog. In a classic article entitled “What the Frog’s Eye Tells the Frog’s Brain,” central players in the Macy group — including Warren McCulloch, Walter Pitts, and Jerry Lettvin — did pioneering work on a frog’s visual system. They demonstrated, with great elegance, that the frog’s visual system does not so much represent reality as construct it (Hayles 1999 131).

Along with Maturana’s (Lettvin *et al.* 1959) corresponding neurophysiological research on perception, “What the Frog’s Eye Tells the Frog’s Brain” anchors autopoietic “reality” in

biological cognition. Andy Clark, contemplating the *strong continuity thesis* (life prefigures mind), initiates a framework I see introducing affinities (Gibson 1986. Wells 2002) in realms where questions such as Turing's "can machines think?" may be extended to potential metabolic/intelligent buildings:

[I]f, for example the basic concepts needed to understand the organization of life turned out to be self-organization, collective dynamics, circular causal processes, autopoiesis, etc., and if *those very same concepts and constructs* turned out to be central to a proper scientific understanding of mind (Clark 2001a 118 original emphasis). . .

. . . we could implement Clark's parity principle (or coupling/parity; Chapter 7. 7.2) between nature and mind to construct observational (ocular and electronic) data streams in order to generate ideas for architecture even factoring in divergent species realities.

The growth of autopoietic-extended design thus has theoretical roots in biology — not only in phenomenology — and its rootstock feeds cognitive functions addressed in autopoietic systems. In this sense, autopoiesis shares with extended cognition a view of what is living and, potentially down the line, how it is living and intelligent. Together, autopoiesis and extended cognition help students read cognitive-state objects and environments. Students and researchers aggregate haptic, tactile, visual, olfactory, and auditory perception that coheres in metabolically supportive performance “indistinguishable from a natural social system” (Maturana & Varela 1980 xxiv). In coherence, the autopoietic unity of systems is indistinguishable from nature, a point Evan Thompson (2007 128) establishes in *Life in Mind*. My aim at this stage then is to explore how defining living and morphological components in intelligence is a primary step for constructing ideas for generative design. This hybridized theoretical channel leads to in-field situated, technologically enabled, learning and design procedures (Clark 2001a. 2008a. Di Paolo 2005. Emmeche 1994. Jonas 1966. Maturana & Varela 1980. Odling-Smee *et al.* 2010. Thompson 2007).

By constructing scaffolding conceptualized in autopoietic and cognitive science coordinated with ideas and procedures derived from Sullivan's pedagogy (Chapter 4), Turing's simulations (Chapter 5), and ideas surrounding anthropologically intelligent environments (Chapter 6), I ply cognitive, environmental, morphological, and computational means to formulate methods (see also *protocol strings* p284) in support of generative architecture. Here, I follow Maturana:

Accordingly, I propose that a collection of autopoietic systems [*student + technology + environment*] . . . [that] through the realization of their autopoiesis, interact with each other constituting and integrating a [design] system that operates as the (or as a) medium in which they realize their autopoiesis, is indistinguishable from a natural [extended phenotype] social system (Maturana & Varela 1980 xxiv).

In the domain of *student + technology + environment*, technology is bordered by student cognition on one side and matter, force, and nature on the other (Clark 2008a). Subsequently, extended cognition interfaces perception, recursion, and feedback among animate and inanimate domains engaging cognitive-state objects in the environment (nature). *Student + technology + environment* — the formal autopoietic unity configured for this thesis, then collaborates with extended cognition to procedurally facilitate methods for students to source data from nature. Those procedures include:

- 1) On-site experience and direct observation of nature for design inspiration and implementation where biological attributes inform biotechnological and metabolic environmental performance for architecture.
- 2) Technology-aided observation providing otherwise unobtainable data.
- 3) Apps providing direct data interpretation for sketches, digital models, etc.
- 4) A theory-based OS protocol supporting digital and physical realms of design generation, communication, and fabrication for visualizing and prototyping metabolically performative materials, infrastructures, and buildings.

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3.3 • E-learning & Smartphone Ubiquity

Deployed for education as cognitively collaborative, smartphones and apps, facilitate technological interventions that enhance student perception during in-field design-research. Brent Davis describes such epistemological processes in education as

[D]eliberate attempts to prompt the emergence and affect the character of . . . phenomena (Davis 2008 58).

Streaming data feeds perception and thinking, enabling their translation into design information. Concurrently, technological sensing and app functionality help students interpret design processes they observe. Autopoietic reliance on data recursion as feedback/feedforth is then emergent: "self-construction through recursive production" (Varela 1981 36). For design,

recursion promotes generative ideas (or sketches, models, etc.) and such recursion may be directed or programmed "to prompt" (Davis 2008) emergence (Bird 2003. Di Paolo 2005. Fenwick *et al.* 2011. Hayles 1999. Maturana & Varela 1980. Weber & Varela 2002).

For design learning and research, generating ideas via nurtured data is instrumental to integrate design conceptualization and visualization (user's metabolism and cognition) with environments as extended cognitive domains. In this recursive context (Varela 1981 37), autopoiesis may be consulted to theorize organization for generative feedback and output (reproductive in the sense of a next-generation design), thus answering Thompson's requirement that an autopoietic system necessarily "regenerates" itself:

One could argue that a minimal autopoietic system requires more than merely a closed and self-producing boundary; it also requires a distinct internal reaction network that regenerates both itself and the [physical/virtual] boundary, and regulates the system's interactions with the outside environment (Thompson 2007 126).

Taking up Thompson's "internal reaction network," autopoietic-extended design places the student in the position of the metabolizing agent activating autopoietic components as unities within a domain: student cognition initiates and aids operational closure involving organisms (agent) and the environment (Fig 14, p145). Thus the "internal reaction network" is bounded by intellectual focus attending to a momentary, domain of concentration whose boundary typologies change as concentration and/or thoughts are processed. Thompson's above quotation implicates a metabolic system existing as an agent (student or designer) in conjunction with nature to animate biological and cognitive autopoietic systems. His words could also support ideas of extended phenotypes (architectures) as constructions interfacing agents, environments, technology, and design systems. Additionally, the words could extend to computational life related to Ricardo Uribe's discussion of autopoiesis in algorithmic programming, living systems, and in open and closed systems:

Autopoietic unities are autonomous unities and hence can relate to other autopoietic unities [structural coupling] only through a reciprocal opening that will tend to create a new, larger unity (which may be either autopoietic or not). For example cells, which are autopoietic unities, become open (allopoietic) [not self-producing] with respect to the multicellular living organism (autopoietic unity) that they integrate, neurons (autopoietic) become open with respect to the nervous system (allopoietic) but not necessarily with respect to other neurons, and ants (autopoietic) become allopoietic

with respect to the anthill (autopoiesis) [and extended phenotype]. Cells, neurons, and ants remain autopoietic with respect to the external observer (Uribe 1981 60).

Recognizing Thompson's requirements through Uribe's text (with my bracketed inserts), distinguishes the spatial concept of "abstract boundary between processes" in autopoietic sense-making and structural coupling as:

... two different kinds of boundary ... at play here. The boundary of the organism (or its brain) as the "intuitive" locus of what we refer to as a cognitive system, and the more abstract boundary between processes, engagements, relations, mechanisms, and systems that deserve the name cognitive and those that do not. The second boundary is never explicitly thematized but it is there (Di Paolo 2008 10).

Thompson (2007) quotes a characterization from Maturana now useful:

A cognitive system is a system whose organization defines a domain of interactions in which it can act with relevance to the maintenance of itself and the process of cognition is the actual (inductive) acting or behaving in this domain [environment]. *Living systems are cognitive systems, and living as a process is a process of cognition* (Maturana & Varela 1980 13 original emphasis).

Functions in living systems, such as "taxic responses of microorganisms, tropisms of plants, or sensory-motor activities of animals" (Thompson 2007 125) are, according to Maturana and Varela, agent-components or sub-agents of "cognitive domain[s]" (Maturana & Varela 1980 119). Taxic, tropic, and sensory responses typify attributes of autopoietic components and unities. Further, they are within the cognitive domain articulated by the unity of *student + technology + environment* that is sometimes conjoined with allopoietic machines; in that way they are *machinically* similar to autopoietic-extended design hybrids intermingling animate and inanimate components:

... allopoietic machines, have as the product of their functioning something different from themselves (as in the car example). Since the changes that allopoietic machines may suffer without losing their definitory organization are necessarily subordinated to the production of something different from themselves, they are not autonomous (Maturana & Varela 1980 80).

In instances of willed concentration paired with technology (m-learning, game playing, checking a map, etc.), the student's autopoietic focus bonds with its allopoietic counterpart (book, game, or map) in a state Clark (2008a) theorizes in extended cognition but that autopoiesis itself does not articulate. The state may be fleeting — lasting only long enough to cognize data as information and generate ideas (Luhmann 2000) — thereafter dissipating to become part of another autopoietic domain (thought or design). In such a scenario, the current conceptualization of generative architecture is incomplete if it is to address living technology. It needs coupling and learning methods as well as working experience with metabolic, cognitive, and natural systems interfacing computation, infrastructure, and materialization before it can legitimately participate in environmental sense-making.

To engage, the unity of *student + technology + environment* loops perception — *cognition-to-nature-to-cognition-to-idea* — to generate constructive data-feeds. This autopoietic-extended design protocol positions autopoietic and allopoietic systems where, to use Thompson's (2007 126) words, "the union of autopoiesis and [extended] cognition is both necessary and sufficient" for life processes to be understood as contiguous and smooth with objects and environments unhampered by dualism. That "necessary and sufficient" stipulation bonds autopoietic-extended design as noted earlier by Uribe, and restated here:

Autopoietic unities are autonomous unities and hence can relate to other autopoietic unities [structural coupling] only through a reciprocal opening that will tend to create a new, larger unity (which may be either autopoietic or not) . . . autopoietic unities can become allopoietic with respect to the larger unity (autopoietic or not) that they integrate; examples are the cell in multicellular organism, the ant in the anthill, the human being in society (Uribe 1981 60).

From my perspective, it is fundamental that autopoietic-extended design avoid dualist traps of mind/cognition or artificial/natural because they prevent autopoietic-to-allopoietic symbiosis (Maturana & Varela 1980. Margulis 1999). In that light, Thompson poetically sketches autopoiesis where:

. . . metabolism is the constant regeneration of an island of form amidst a sea of matter and energy" (Thompson 2007 152).

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Chapter 4 • Louis Sullivan's *A System of Architectural Ornament*

I insist strenuously, that a building should live with intense, if quiescent, life, because it is sprung from the life of its architect. On no other basis are results of permanent value to be attained (Sullivan 1979 184).

Louis Sullivan's words, "sprung from the life of its architect," sketches a transcendental vision autopoiesis can now articulate if we conceive of architecture encompassed by nature and rendered enactive by the agency of the architect. Furthermore, Sullivan's proto-autopoiesis exhibits structural organization and component assembly compatible with Maturana and Varela's (1980) theory involving units, composites, domains, structural coupling and self-production (Varela 1981). This chapter then initiates a discussion of life, metabolism, intelligence, and AI pertinent to architectural generation foreshadowed by Sullivan's (1967. 1999) *A System of Architectural Ornament: According with a Philosophy of Man's Powers*.

My analysis eventually intersects with a proposal for advanced, smartphone enabled, biomimetic architectural practices (Sullivan 1967. 1979). It places *A System* in the framework of universal environmental computation (Copeland 2012. Saunders 1992. Turing 1950. Wells 2004), relating nature to pattern, metabolism, sense-making, form, morphology, and genetic algorithms (Floreano & Mattiussi 2008. Frazer 1995. Thompson 1992. Wolfram 2002). Later, autopoietic organization accommodates students and designers as environmentally embedded partners in an emerging system for research (Chapter 7 & Appendix 1. 2) in which it is necessary to accredit life and cognition as extending recursively between design and nature (Dawkins 1982. Langton 1988. Maturana & Varela 1980).

Originally autopoiesis theorized biological cells and organisms, only sketchily discussing how the theory *might* function in complex environments and social systems.

What we are saying in the case of autopoiesis is that if we could follow all the appropriate contingencies, the [domain's] biological phenomenology would unfold from the autopoietic mechanism (Maturana 1981 42).

That process of unfolding is applied to design thinking and generative architecture. Five-years after Maturana and Varela's book, John Frazer's *An Evolutionary Architecture* pioneered a parallel but more technological trail declaring:

... architecture is considered as a form of artificial life, subject, like the natural world, to principles of morphogenesis, genetic coding, replication, and selection (Frazer 1995 9).

Much earlier, in 1924, Sullivan's *A System of Architectural Ornament* prefigured both *Autopoiesis and Cognition* (Maturana & Varela 1980) and *Evolutionary Architecture* (Frazer 1995). From this ancestry, it's instructive to note that Frazer opened *Evolutionary Architecture* with a long epigraph from *A System* introducing the metaphor of the "seed" as generative (Frazer 1995 9). *A System* (1999) had looked to the seed as metaphor supplying "the will to power: the function of which is to seek and eventually to find its full expression in form." Sullivan's shades of Nietzsche thereafter drove code-like geometry and rule-based (but not computational) plant morphology for design pedagogy based in nature. In *A System's* drawings and text I find a prototype for generative design and learning systems and reference them to autopoiesis for a symbiotic take on biogenerative architecture as living technology (Armstrong 2012. Bedau *et al.* 2013. Margulis 1999. Spiller 2009. Weinstock 2006a b).

If paper inscriptions — architectural drawings and sketches in this case — carry and transmit ideas and code to participate in cognition, they do so phenomenologically in ways cognitive science is attempting to explain (Clark 2008a). I expect no controversy in stating that drawings sometimes alter, and frequently extend, cognitive perception to account for generating ideas and translating concepts — in this sense drawings are cognitive-state objects (Clark 2008a. Dawkins 1982. Frazer 1995. Turner 2000). Importantly here, paper inscriptions and drawings also connect theories of autopoiesis and extended cognition I consider in Chapter 7 (Clark 2001. Di Paolo 2005. Maturana & Varela 1980. Weber & Varela 2002). That expanded context is consistent with Sullivan's transcendental sentiments concerning life, spirit, and architecture as I present them (Menocal 1981. Sullivan 1967. 1979) interfacing computational intelligence, ALife (Bedau 2003), and synthetic biology (Bedau *et al.* 2010). In this light, Sherman Paul found in Sullivan's work, "both continuity and transformation: the idealism of transcendentalism — its reassessments of the creative power of man — ... naturalized in an equally idealistic pragmatism" (Paul 1962 ix).

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A System appears to be a formal rule set, a graphic and text forerunner of digital simulation and algorithmic design, a condition mirrored today in Rieffel's soft robotics and their functions via genotypes and phenotypes:

Rule sets describe a developmental *process* and thus they are an *indirect encoding* of a ... physical phenotype ... With a grammar as a genotype, an evolving population simply

consists of a collection of these grammar genotypes (Rieffel *et al.* 2013 155 original emphasis).

While *A System* is analog, transcendently poetic, and directed to ornament, it nevertheless demonstrates sequenced drawing rules paired with geometry and bio-observation constructing “grammar genotypes” bonding through phenotypes and expressed in extended phenotypes (Dawkins 1982. Hansell 2005. Rieffel *et al.* 2013. Turner 2000). *A System*’s rules could be translated to programming, research organization, and generative design (for a simplified comparison see: Heumann 2013. Fig 22, p184). I speculate, based on Turing’s morphogenetic research (1952. 1953), that, had he known Sullivan’s (1999) work, he might have recognized *A System* as morphologically rich with rule-set relations to his own phyllotaxis, embryological, and reaction-diffusion drawings and simulations (Chapter 5). As a consequence, Turing might have seen Sullivan’s proto-shape grammars and rule-derived drawing lessons as primary steps for biology-to-code computational simulations (Saunders 1992. Swinton 2004. 2013. Turing 1936. 1950. Thompson 2007).

Sullivan’s step-by-step drawings (Figs 15-19, pp157-161) can be read as analog cousins related to computation and algorithmic simulation (Floreano & Mattiussi 2008. Prusinkiewicz & Lindenmayer 1990. Deussen & Lintermann 2010. Turing 1952. Wolfram 2002). Noteworthy too, is Sullivan’s use of biological metaphors informing architecture with notions of animate design that computation opened in disciplines involving digital simulation, computational botany, and living technology. Statements such as:

... our architecture must become a living force (Sullivan 1979 66)

or,

... an office being similar to a cell in a honeycomb (Sullivan 1979 203)

hint at his relationship to 19th-century transcendental art, science, and philosophy as they played out in Sullivan’s last decades.

Narciso Menocal observed that: “Sullivan made his work a reflection, or perhaps an extension, of the transcendent generative process” (Menocal 1981 31). Through Sullivan’s own words and transcendental concerns, I induct him into the company of Maturana & Varela’s theory of autopoiesis and Clark’s extended cognition hypothesis (Clark 2008a. Maturana & Varela 1980. Menocal 1981. Twombly & Menocal 2000). *A System*’s drawings and words suggest

an autopoietic mind-set conspicuous as an architectural landmark, demonstrating concerns with the synthesis of nature, architect, and theory:

A great work, for us, must be an organism — that is, possessed of a life of its own; an individual life that functions in all its parts; and which finds its variations in expression in the variations of its main function, and in the consequent continuous, systematic variations in form, as the organic complexity of expression unfolds: all proceeding from one single impulse of desire to express our day and our needs (Sullivan 1979 160).

Consequently, Sullivan contextualized the organic:

Organic, we should, at the beginning fix in mind the values of correlated words, organism, structure, function, growth, development, form. All of these words imply the initiating pressure of a living force (Sullivan 1979 48).

The vision Sullivan authored in *A System* mediates buildings, theory, and nature expressing his views for architectural communication. Before digital computers, he coded nature-to-ornament as a means for creating an architectural surface that engaged dialogue with the person on the street. Sullivan (1979 105) said: "a building is an utterance" and programmed architecture and design learning as a medium of rule-based, graphic-centered communication. In this sense Sullivan's finds company with Patrik Schumacher in emphasizing communication:

It is the stream of simultaneous and successive communications that constitutes architecture as [an] autopoietic system. The theory of architectural autopoiesis theorizes (designed) buildings and the (designed) spaces within and around them as a crucial type of autopoietic communication (Schumacher 2011 3).

A System has always offered aesthetic and morphological insight into, and through its methods and drawings. It replicates Sullivan's ideas in images and text when he distilled thinking-to-drawing processes in step-by-step graphic instructions for sourcing data from nature as inspiration for architecture. Those instructions — teachings — prefigure an aspect of rule-based computability in his methodology that is consistent with the theory of extended cognition (Figs 15-19, pp157-161).

Sullivan's drawings are feedback-driven, their narrative technology (Hayles 1999. 2012) is supported by morphological communication enacted in drawings. Turing's drawings are, by

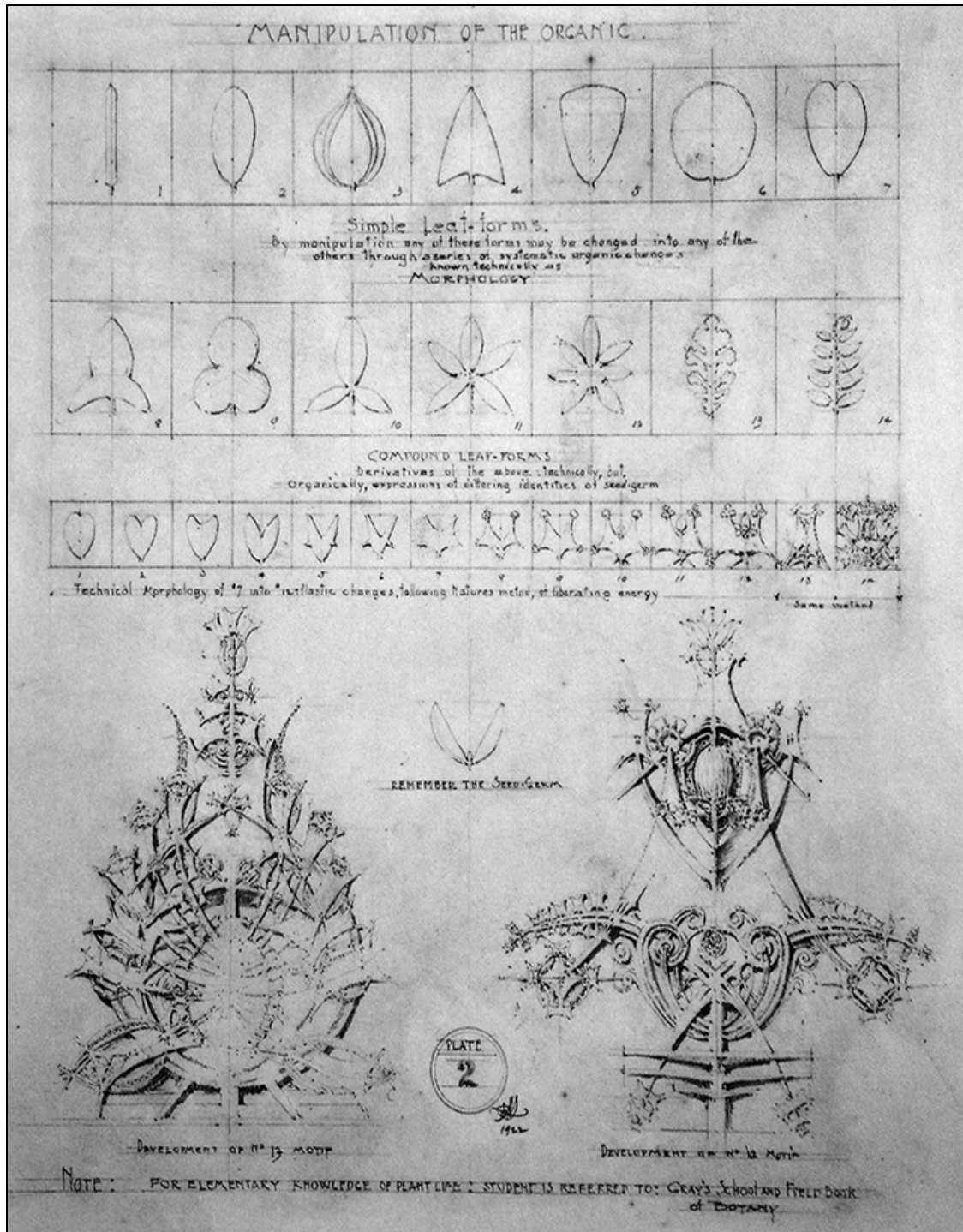


Fig 15. Morphological proto-shape grammar.

Louis H. Sullivan. American, 1856-1924.

System of Architectural Ornament: Plate 2, Manipulation of the Organic, 1922-23.

Graphite on Strathmore paper. 57.7 x 73.5 cm (22 3/4 x 29 in.)

Commissioned by The Art Institute of Chicago. 1988.15.2. ©The Art Institute of Chicago.

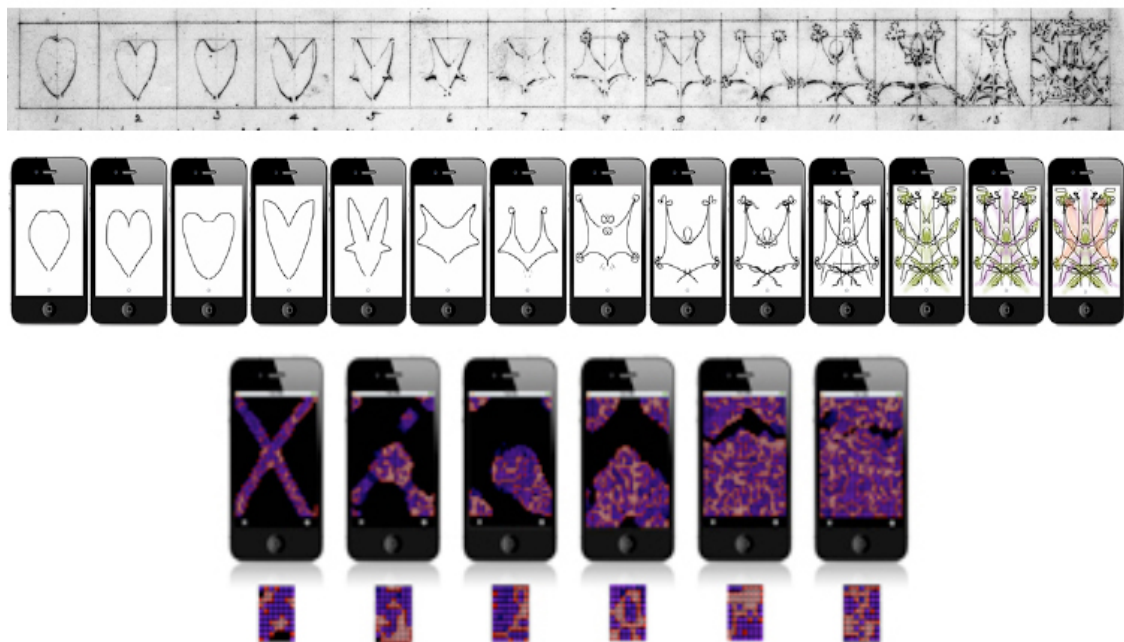


Fig 16. Top Detail, Plate 2. *A System of Architectural Ornament*. 1924. "Technical morphology . . . plastic changes, following nature's method of liberating energy." Louis Sullivan. (See Plate 2 p154). Louis H. Sullivan. American, 1856-1924. *System of Architectural Ornament*: Plate 2, Manipulation of the Organic, 1922-23. Graphite on Strathmore paper. 57.7 x 73.5 cm (22 3/4 x 29 in.) Commissioned by The Art Institute of Chicago. 1988.15.2. ©The Art Institute of Chicago. Middle. iPhone exercise to understand graphic transformational morphology in Sullivan's *A System*. Bottom. iPhone screen captures of Conway's *Game of Life*, illustrating rule-based digital systems of generative ALife.

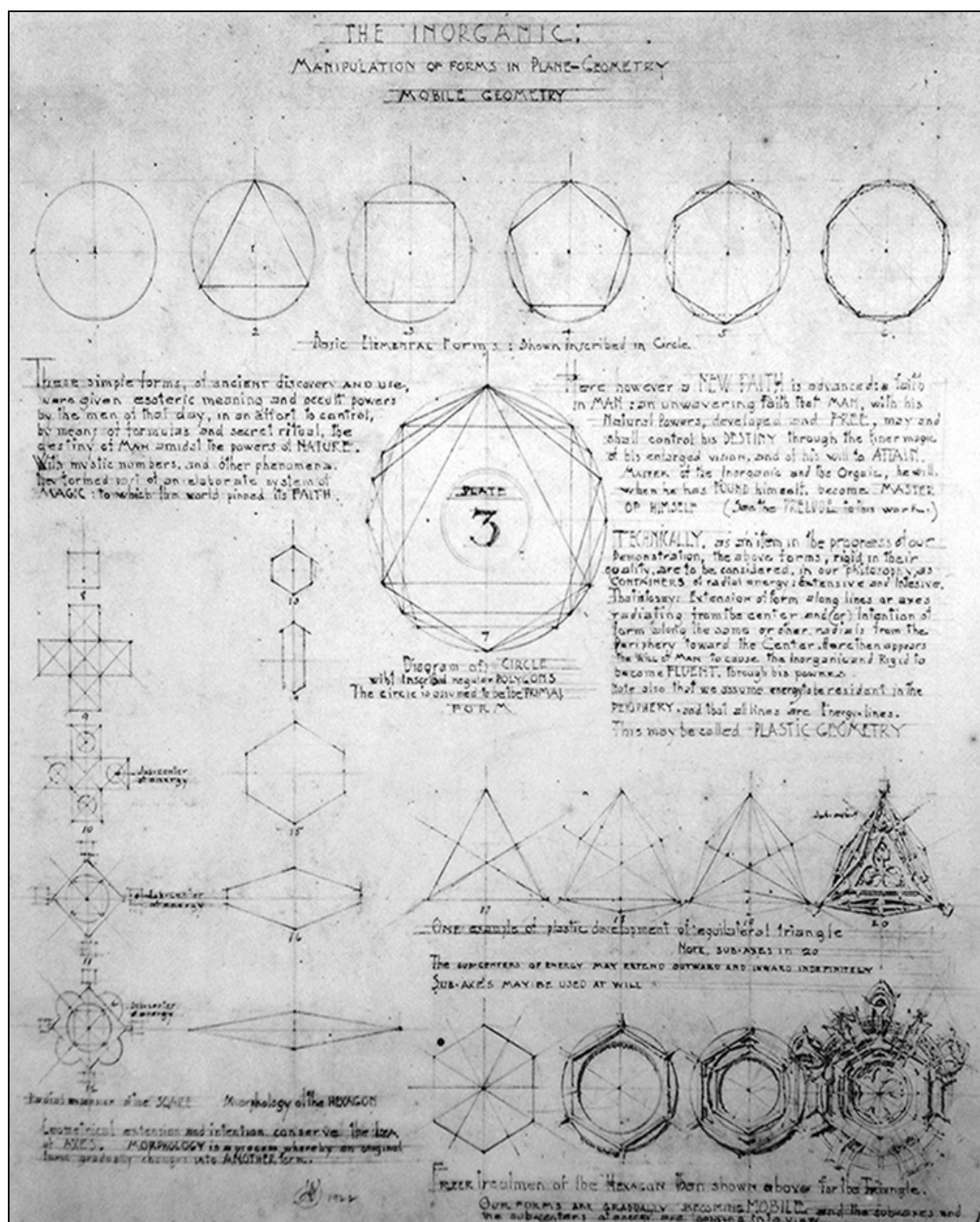


Fig 17. Louis H. Sullivan. American, 1856-1924. *System of Architectural Ornament*: Plate 3, The Inorganic, 1922-23. Graphite on Strathmore paper. 57.7 x 73.5 cm (22 3/4 x 29 in.)
Commissioned by The Art Institute of Chicago. 1988.15.3. ©The Art Institute of Chicago.

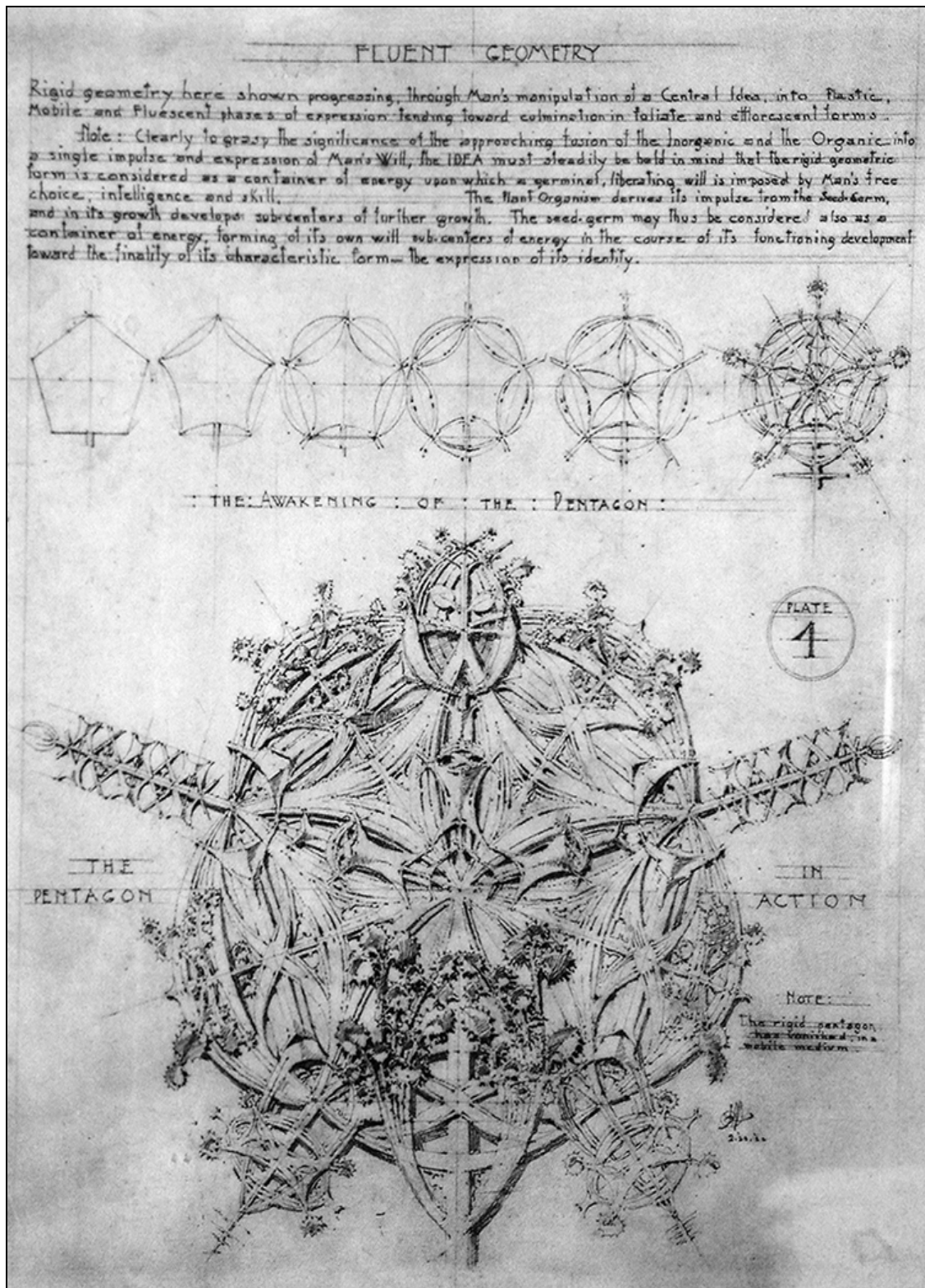


Fig 18. Louis H. Sullivan. American, 1856-1924. *System of Architectural Ornament*: Plate 4, Fluent Geometry, 1922-23. Graphite on Strathmore paper. 57.7 x 73.5 cm (22 3/4 x 29 in.) Commissioned by The Art Institute of Chicago. 1988.15.4. ©The Art Institute of Chicago.

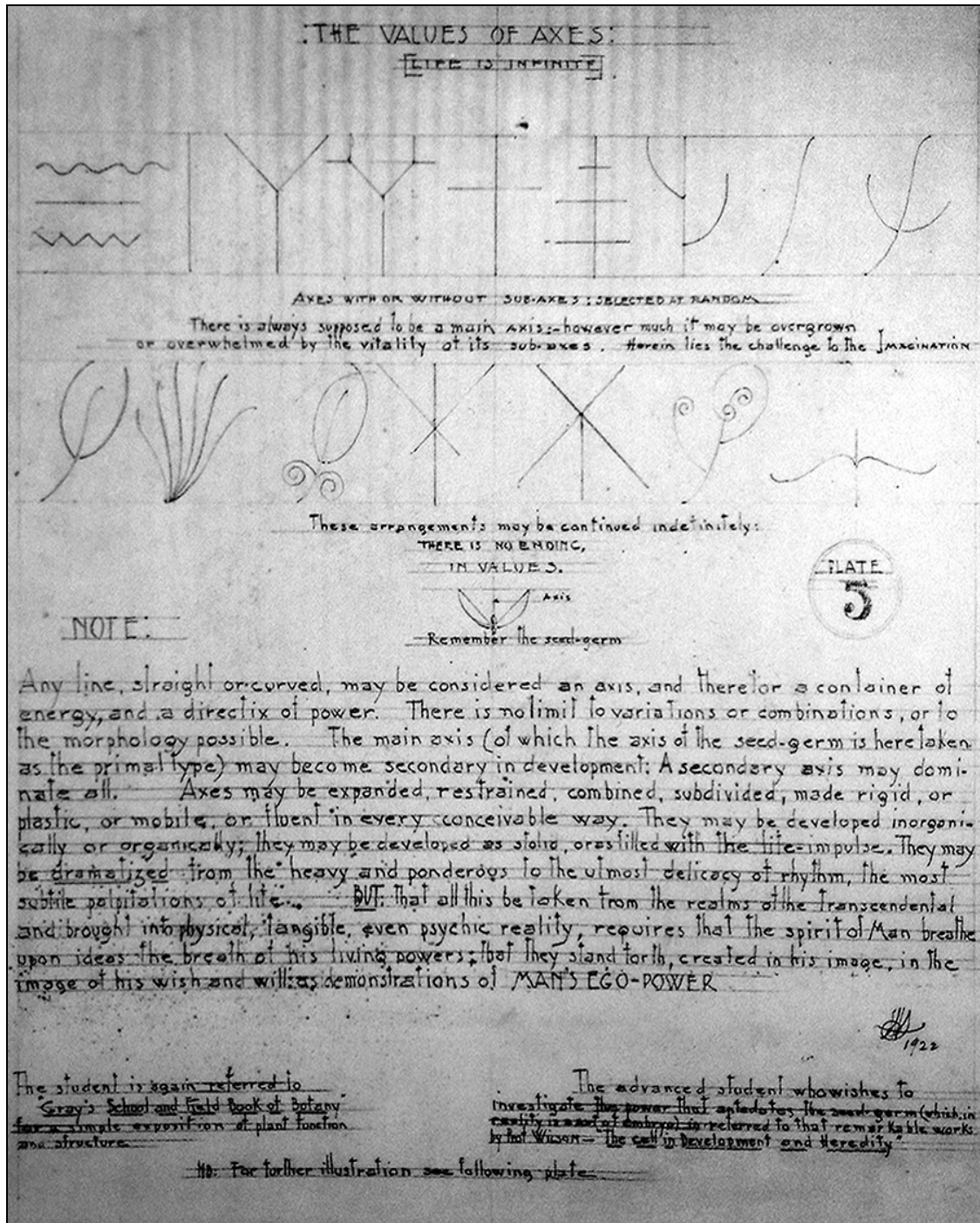


Fig 19. Geometric proto-shape grammars.

Louis H. Sullivan. American, 1856-1924. *System of Architectural Ornament*: Plate 5, The Values of Axes (Life is Infinite), 1922-23. Graphite on Strathmore paper. 57.7 x 73.5 cm (22 3/4 x 29 in.) Commissioned by The Art Institute of Chicago. 1988.15.5. ©The Art Institute of Chicago.



Fig 20. Merchants' National Bank. Grinnell, Iowa. 1914. Louis Sullivan. Cast-terracotta ornament as near-literal reproduction of Sullivan's 2D drawings as 3D architectural expression and communication. As in his *System's* drawings, morphological organic forms interact with geometric constructions for architectural performance. Photos: Dennis Dollens.

contrast (Chapter 5) computationally generative, digital and/or hand-drawn graphics factoring in morphological performance for use in programming intelligence in machines (Saunders 1954. Swinton 2004. Sullivan 1999. Turing 1950). Both Sullivan's and Turing's drawings are research oriented with intentions to support insight and/or function. Demonstration lessons in *A System*, like those in a comicbook, use sequential graphic cells communicating active movement — animate development (Fig 19, p161 top). Sullivan's storyline transports morphological properties of plants and geometries into design elements for architecture, while the narrative of those drawings (and later architectural ornament) become his building's expression and dialectical interface. Maturana & Varela 1980. Sullivan 1967. 1979).

Likewise, through geometries and proportions found in nature, Turing's drawings and digital simulations, analyzed in the next chapter (Figs 24-27, pp188-191), mediated vision, mathematics, and machine intelligence addressing nature-to-computation. Turing's corresponding and embedded narratives translate between nature, code, machine, mathematics, and human intelligence by means of which I project the redeployment and metaphorical reanimation of Sullivan's work for education today (Copeland 2012. Hayles 2012. Teuscher 2004. Michie 2002).

The procedural process *A System* (1999) illuminates looms historically and aesthetically important because it illustrates an individual architects' subjective aesthetic in a reproducible method intended to speak to students. *A System* thereby encourages students to extrapolate from Sullivan's easily understood translation of nature into an architectural performance of their own (Sullivan 1967. 1999). As a teaching device, its little-used lessons are conduits for architectural design and the transportation of ideas collaboratively realized through nature by means of in-field observation and traditional drawing (Menocal 1981. Paul 1962).

Sullivan's drawings record *A System's* hybridization of botanic morphology and geometry for design-learning scaffolds. Coincidentally, and only touched upon here, Sullivan believed architecture to be an expression of an era's zeitgeist; a container of social and democratic values (Paul 1962. Sullivan 1961) capable of transmitting the embodied spirit of the people (Luhmann 2000. Sullivan 1979). Considered in the domain of Sullivan's writings, *A System* still teaches from its embedded vision coded in line and form (Clark 2001. Luhmann 1996. Thompson 2007. Wells 2004). In this respect (mimetic and perceptual), I hook Sullivan's discussion of social systems, nature, and communications with current research involving intelligence, selection, extended cognition, autopoiesis, and digital biomimetics (Clark 2008a. Maturana & Varela 1980. Sullivan 1967. 1979).

Historically, *A System* reveals a nascent methodology for integrating morphological design into differently focused architectural organization and communications that are today

compatible with ecological and social intentions realizable as components of buildings (Sullivan 1896. 1999). The book's plates, when engaged by a reader, reanimate and extend visualization potential of nature that Sullivan embedded more than a century ago in his facades and last writings. For students, *A System* recontextualized as autopoietic and filtered through recent theories of extended cognition, paves a road back through history to morphology and forward to sustainability, bioremediation, and digital systems — a road extendable in mobile app pedagogies.

Sullivan did not foresee computational generative architecture, yet looking through the lens of autopoiesis we may safely say he envisioned an analog generative method still informative. That method entails a step-by-step articulation we access in many of his sequential drawing lessons where drawing-cells progressively evolve from cell one to cell two to cell three, etc. as part of an organic development process Plate 2 (Fig 15, p157). Discussing examples of form development, *A System* demonstrates morphological shape transformations informed by the science of its day (Sullivan 1967. Thompson 1992/1917. Wilson 1999), and here it opens itself to contemporary analysis involving algorithmic generation (Deussen & Lintermann 2010. Floreano & Mattiussi 2008. Wolfram 2002). Therein *A System's* transformations of shape and its algorithmic potential align with Turing's morphogenetic research (1950. 1952), with Lindenmayer's algorithms (1990), Alexander's early pattern language (Alexander *et al.* 1968), and Xfrog's L-systems interface (Deussen & Lintermann 2010. Prusinkiewicz & Lindenmayer 1990. Saunders 1992).

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Slightly predating *A System*, Sullivan's late bank buildings (Weingarden 1987) serve as physical embodiments of his theory (Fig 20, p162). Those small commissions substantiate his ideas of morphological transformations suitable for development and materialization in architecture (Menocal 1981. Paul 1962). By *substantiate* I mean Sullivan's architectural processes for realizing drawing in solid form: *conception-to-image-to-material-to-architecture*. These transformations — witnessed in the uncanny likenesses of his 2D drawings to their subsequent 3D architectural panels — testify to a cognitive-to-material transference of design from drawings to communicative architectural forms. In this frame, *A System* was a precursor to autopoietic-extended design processes rooted by Sullivan's conviction that buildings could live and express nature through the mind of the architect (Menocal 1981. Sullivan 1979 184).

The theory Sullivan used to organize and ornament his Chicago School tall buildings (Menocal 1981. Sullivan 1886) and the later bank facades (Weingarden 1987), predate, as well as underpin, *A System's* culminating pedagogical efforts to express ways that buildings *might* live

(Sullivan 1979 184). And, although he published earlier writings dealing with design education, *Kindergarten Chats* (1979/1918) for example, they do not hint at the graphic, generative methods found in *A System* (Sullivan 1967. 1979). While Sullivan's buildings substantiate the drawings, the book's drawings (metaphorically) *substantiate*, stand under or behind, the buildings. *A System's* how-to drawings *under-stand* Sullivan's architecture in an essential way, as captured in the Greek root "*epistamai*: 'I know how, I know' literally "I stand upon" (Online Etymological Dictionary 2014). Ironically, in a book discussing the creation of ornament, none of the drawings are merely decorative or ornamental.

Reading *A System's* plates, I find 2D schematic images and methods: *thought-to-eye*, *eye-to-hand*, *hand-to-paper*, and *paper-to-generative pedagogy*. Sullivan's handwritten texts annotating the drawings (Sullivan 1990) reinforced his transcendental outlook and narrative voice — sometimes foretelling those of Jonas (1966). The captions and comments also reinforce my interpretation of the drawings as embedding serial generative and narrative data. In this species of metadata, as seen in Plates 2 and 3 (Figs 15, p157. 17, p159), the progressive developmental methods are applied to plant morphology to evolve "Simple Leaf-Forms." And, at Plate 5 (Fig 19, p161) we find Sullivan sequencing hybridized line-forms he calls "axes with or without sub-axes." Essentially, both Plate 2 and Plate 5 depict shape grammars from which morphological drawing growth is demonstrated — Plate 2 generates leaves (surface or planer forms) and Plate 5 generates branches, tree structures, and geometries (grids and matrices).

Beyond architecture, these proto-grammars and instructional narratives process Sullivan's attempt to systematize nature's availability for input to design generation resting on observations from nature. Systematized generation is something Turing also attempted (Chapter 5) in what is, perhaps, the earliest (Reinitz 2012) computer-aided biological simulations (Copeland 2012. Swinton 2004. Sullivan 1999. Teuscher 2004). In this realm of computational life and systematized morphology, autopoiesis gives credence to my introducing Sullivan's generative *System* grammars to Turing's algorithmic drawings and computer simulations. From that paralleling introduction, I grandfather *A System* into design's genealogy crediting Sullivan's methods as analog precursors to digital-botanic simulation and biogenerative architecture.

I aim to establish where current design, architecture, biological theory, machine intelligence, and morphology intersect with research, learning, and technology — for example, in L-system plant generation (Lindenmayer 1968), app drawings (Heumann 2013. Fig 22, p184) or stereo lithographic (STL) models (Fig 7, p78). I ask how we may ecologically activate new protocols by digitally reincarnating an old system. Doing so, I follow Slavoj Žižek's endorsement of history as a contemporary filter:

... the only way to grasp the true novelty of the new is to analyze the old. If [something] is really an eternal idea ... it is eternal not in the sense of a series of abstract-universal features that may be applied everywhere, but in the sense that it has to be re-invented in each new historical situation (Zizek 2009 6).

Looking back to Sullivan thus brings into view historical relationships between scientists, mathematicians, and architects, including D'Arcy Thompson, Alan Turing, and Christopher Alexander (Alexander *et al.* 1968. Thompson 1992/1917. Turing 1950. 1954). One trail through this unusual grouping leads from Maturana and Varela's sense of unity/unities to my grouping of *student + technology + environment* as conjoined but not inseparable autopoietic units (Maturana 1981. Varela 1981). This course of learning is also part of architecture's autopoietic continuum as per Sullivan's insistence that: "a building should live" (Sullivan 1979 184).

For current design learning what's needed, on the one hand, is a conceptual shift in order to articulate cognition as distributed in nature, centered in metabolic life, and configured intentionally — tunable — by individual designers or students (Clark 2008. Coyne 2010. Di Paolo 2005). On the other hand, biodigital learning requires data from nature (Turner 2000) as well as from technology (smartphones) that inspire perception and validate visualizations (Weinstock 2006a). Such input is, of course, perceptually/cognitively determined and interpreted through the researcher's experience (Barnett 2007. Clark 2008. Di Paolo 2005. Fenwick *et al.* 2011. Lettvin *et al.* 1959. Luhmann 2000. Rosenblueth *et al.* 1943. Webb 2009).

For students, such processes may be aided by mobile and extendable technology, coupled when apps and digital mediation are brought to bear as virtual spaces of production for class communication and participation. In this assemblage, the autopoietic unity of *student + technology + environment* is centered in the designer's sensory domains with cognitive and sensory functions distributed through objects, technology, and environments (Clark 2001. 2008. Di Paolo 2010. Thompson 2007. Varela 1979). At different ranges and intensities the autopoietic unity of *student + technology + environment* senses, perceives, and processes design data/information collaboratively with nature (Clark 2008a. Di Paolo 2005. Maturana & Varela 1980. Weber & Varela 2002). *A System* may then be looked to as a method translating natural systems data into design-relevant information (Luhmann 2000. Varela 1981), with no need on the students' part to mimic Sullivan's aesthetics or metaphysics (Clark 2008a. Coyne 2010).

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Sullivan's DIY guidance, his pre-computational logic for articulating architectural forms and processes for meaning and communication are still extractable. His lessons may be recommissioned for digital visualization and metabolic-informed design learning. In this case, Sullivan's drawings rather than his metaphysical concepts yield analog processes akin to Turing's codes, drawings, and generative simulations (Deussen & Lintermann 2010. Floreano & Mattiussi 2008. Prusinkiewicz & Lindenmayer 1990. Wolfram 2002 939). Through the scaffold of autopoietic-extended design, *A System's* evolved rules help question how metabolic life relates to generative architecture. If metabolism and architecture are related, the rules assist in filling the gap between conceptualization, research development, and design experimentation (Jonas 1965. 1966. Maturana & Varela 1980. Sullivan 1990. Thompson 2007. Varela 1979).

Sullivan's *System* references two science books, one an advanced university text on cellular morphology, Beecher Wilson's, 1896 *The Cell in Development and Heredity* 1896); the other, a field guide to botany first published in the late 1840s with its most recent reprint dated 2001 (Asa Gray's, *Gray's School and Field Book of Botany*). Lynn Margulis called Wilson's book "a masterpiece," reading the 1928 edition she explained, Wilson: "talked about the similarity of the cell organelles, the plastids, and mitochondria, to free-living microbes" (Margulis 1999 33). These two books are important because they connect Sullivan's works with contemporary scientific findings and theories, while his transcendental roots branched through philosophy sourced in, for example, Emerson, Nietzsche, Swedenborg, Taine, Thoreau, and Whitman (Menocal 1981. Paul 1962. Taine 1896. Twombly & Menocal 2000). The architecture Sullivan sought to teach with methods that E.O. Wilson (1999) later called *Consilience*, and Margulis (1999) called *symbiosis*, was a synthesis of biological life more likely considered today via non-linear systems, emergence, and complexity theory (Bird 2003. de Duve 2002. Fenwick *et al.* 2011. Mason 2008a. b).

Autopoiesis might at first seem to preclude the consideration of *A System* because the autopoietic book lacks metabolic life. In addition, Sullivan's subjective, transcendental language lessens his *System's* rigor by implanting mystical narrative into a rule-based process (Hayles 2012. Menocal 1981. Sullivan 1967. 1979. Twombly & Menocal 2000). Nonetheless, his plant/geometry assemblies exhibit surprising autopoietic and computational properties and potential. *A System* engages student observations variously open to other morphologies: trees, shells, tendrils, skeletons, cells, seeds, etc., as cognitive-state objects available to study. Moreover, *A System* allows for translating those observations via analog (or digital) actions as form-finding corresponding to, or overwriting, geometries and programmable branching, spiraling, vining, climbing, and twining (Deussen & Lintermann 2010. Floreano & Mattiussi 2008. Mattheck 1998. Turner 2000). And, since Sullivan assigned narrative value to both

geometry and plants using shape-coded icons (Figs 15-20, pp157-162), he opened his morphological lessons as hybridizing design events to students:

By manipulation any of these forms [the drawing icons] may be changed into any of the others through a series of systematic organic changes known technically as "morphology" (Sullivan 1967 Plate 2 Fig 15, p157).

Overall, the *System's* instructions express Sullivan's identification of organic and inorganic functions to be interpreted through graphic and symbolic vocabularylike icon-forms representing stems, leaves, and seedpods. His materially embedded, allopoietic graphic signs communicate the vision he articulated in: "The Tall Building Artistically Considered" (Sullivan 1896) as they await engagement with an observer/agent to initiate communication.

In another example, his study of axes and axial flow Plate 5 (Fig 19, p161) resembles descriptive digital tree branching found in later computer graphics organized along principles that resemble Lindenmayer's (1968) rewriting systems (Deussen & Lintermann 2010. Floreano & Mattiussi 2008. Prusinkiewicz & Lindenmayer 1990. Sullivan 1967). With algorithmiclike potential, *A System* functions to create geometric matrices capable of integration with a building's structural grid or cage frame (Deussen & Lintermann 2010. Prusinkiewicz & Lindenmayer 1990. Todd & Latham 1992. Wolfram 2002). And, within *A System*, directional (tropic or attractor) geometries reinforce structural and organizational forces to illustrate latticelike trellises and ornamental frameworks that host the drawing's and building's depiction of organic life. Those grids, functioning akin to extracellular matrices, what Varela and Frenk (1987 79) called "morphocycles," supports adhesion, communication, and differentiation simultaneously servicing what Sullivan called "efflorescence" (Sullivan 1967 Frontispiece), the *botanically growing* plant forms depicting life and spirit emerging from his lessons or sculpted into his building facades.

Even without computation, Plate 5 (Fig 19, p161) illustrates axial, subaxial, and nodal fluidity familiar today as geometric procedures in 3D software, animation, and rule-based generation (Deussen & Lintermann 2010). As sequential processes, Sullivan's graphic instructions point up strings of non-uniform but recursive developments of form (growth) related to algorithmic processes embedded in geometry and nature (Deussen & Lintermann 2010. Floreano & Mattiussi 2008. Prusinkiewicz & Lindenmayer 1990. Turing 1950).

Did Sullivan's knowledge of science and nature successfully blend his ideas with animate botanical systems into what today could be considered an ancestor to autopoietic generative architecture? Did he support his assertion that "architecture must become a living

force?" (Sullivan 1979 66). It may be too late to answer authoritatively such broad questions dependent on a better knowledge of his reading and study materials. What if I ask, instead, does Sullivan's architectural ornament and drawing system still productively communicate his amalgamation of geometry and botanic growth? This third question may be asked of computation and machine output in general, as we see in the section on Turing (Chapter 5). My query is answered affirmatively if *A System* successfully continues to find application and students — does it attract readers and generate ideas to justify its own self-production?

I take as self-evident that Sullivan's knowledge of botany and morphology enriched *A System* with communicable data affecting autopoietic-friendly rules for design that are still operative today (Menocal 1981. Sullivan 1967. Twombly & Menocal 2000). When I intermix his rules and drawing gestures with technologically harvested natural data from smartphones and apps, I configure them within a new design OS. Toward an OS, *A System* illustrates teaching practices in which designers may appropriate environmental, sustainable, technological, and cognitive systems guided by integrated, tunable, learning procedures (Coyne 2010). *A System* is then an antique design-generator capable of influencing current biodesign and learning (Zizek 2009) through its embedded analog data. Moreover, I think that *A System*, as a manifesto, should be redeployed, given new life, in a context where advanced technology is substituted for Sullivan's transcendentalism.

From a technological point of view, mobile devices and Internet services as well as GPS, drawing apps, hand-held 3D scanners, augmented-reality apps, mobile CAD apps, and network communication offer opportunities for research connectivity that was unimaginable in Sullivan's time. But, equally unimaginable is a social landscape without networked, smartphone connectivity. *A System's* Plates 2, 3, and 5 (Figs 15, p157. 17, p159. 19, p161), chart potential for learning, reanimation, and redistribution of Sullivan's pencil-inscribed, idea-embedded processes into digital realms. This technological reframing of his ideas henceforth opens *A System* to hybridizing influences from Maturana and Varela (1980), Clark (2008a), and Turing (1950).

Sullivan's ideas transcend one-to-one decoding. He proposed autopoieticlike data communicated from nature channeled through the architect and the materialized building to the person on the street (Sullivan 1979). His design/architecture still exists as physical and pedagogical communication vectors transmitting his vision to observers engaging his drawings and façades.

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4.1 • Autopoietic Affinities

A System must meet these conditions to be autopoietic:

- 1) Component articulation and assembly.
- 2) Organization of components into unities.
- 3) Organization of unities into domains.
- 4) Recursive actions between components, unities, domains.
- 5) Structural coupling between agent (metabolic, synthetic life, or AI) components, unities, domains, and environments.
- 6) Boundary formation.
- 7) Self-monitoring (observation/homeostasis).
- 8) Self-maintenance.

But, *A System* only meets these requirements when connectively metabolized (coupled) with an agent (reader, designer, or student cognition) — otherwise conditions #5-8 are not met. Thus, *A System* is only autopoietically active when it's cognitively engaged. Nevertheless, that engagement is not trivial in terms of agent (student) structural coupling with objects in the environment. When not cognitively engaged, *A System* may be thought of as inactive — between autopoietic and allopoietic — in the way of seeds: dormant but viable.

The creation of an autopoietic domain then sets the stage to delineate a comprehensible communication system between *student + technology + environment*. Autopoietic components comprising unities, and unities assembling domains, subsequently create operationally closed (Varela *et al.* 1992) (Chapter 1. 1.5) working milieus for interaction and boundary formation between cognition and objects (Clark 2008a). Boundary formations provide one category of organization in domain-defining interactions among the components of a system responsible for data communication (Maturana & Varela 1980). Domain processing is then instantiated through the designer's cognitive input involving nature, optical and sensory focus, object/environment, and technological data-feeds nourishing idea generation. This example of autopoietic networking allows for teleological input/output (Nagel 2012) thereby amending Maturana & Varela's (1980) original theory as predicated on Weber & Varela's (2002) and Di Paolo's (2005) revisions fusing-in adaptability and sense-making (See Di Paolo quote, bottom p138).

The operational procedures I build from sourcing *A System* extend Sullivan's communication and morphology as input systems for the generation of information for architecture into new digital realms (Clark 2008a. Lettvin *et al.* 1959. Turing 1952). But, since design, like nature, is a punctuated, ongoing process, its domains (as part of nature) have periodic levels of activity involving long-term adaptivity (Di Paolo 2005) — the same goes for student focus and concentration as it moves between differing aspects of project research to

take in and manage data. In autopoietic biology this periodicity appears as intervals of metabolic activity, switching production, and rest/dormancy. I register the first stages of generative design then in this autopoietic frame as a paradigm shift that emerged in the twelve-year period between Sullivan's (1924) *System* and Turing's (1936) universal machine (Chapter 5), maturing into generative architecture's infancy after Turing's early-1950s biocomputational simulations (Dollens 2014. Reinitz 2012. Swinton 2004).

Sullivan's view of morphological symmetry was aesthetically romantic and transcendental (Menocal 1981) requiring stylization. Turing (1952. 1953) on the other hand, programmed mathematical symmetry-breaking code necessary to explain the development of, for example, a symmetrical fertilized egg developing into a bilaterally symmetric organism (Floreano & Mattiussi 2008 320-321. Prigogine & Nicolis 1967. Richards 2013. Turing 1952). So, while Sullivan beautifully illustrates a practice of searching nature for symmetrical and asymmetrical development, observational method, and techniques for creating botanic semblance, Turing's research, vis-à-vis generative architecture, marks a start for nature-to-algorithm observation, botanic simulation, and embryological generation/symmetry-breaking (Dollens 2014. Reinitz 2012. Richards 2013. Swinton 2004. Turing 1952. 1953).

Contrasting Sullivanlike observation and methodology with Turinglike observation/computation, the student or researcher has options for design "tuning" (Coyne 2010) not available to either Sullivan or Turing (Sullivan 1999. Turing 1952). Iterations of Sullivan's and Turing's drawings document developmental changes from different epochs of visualization, yet they constitute some of the earliest permutations of generative design when biological simulation is factored in (Reinitz 2012).

If today *A System* is activated for autopoietic-extended design, the student/designer triggers observation-to-drawing processes with nature in which sensing and interpreting contribute to generative visualization or physical composition. At completion of observational processes, the autopoietic-extended OS pauses to begin again with the same student starting another phase. In this protocol, *A System* helps each student evolve design by temporarily aiding that student's agency-to-environment acquisition of raw data. It steps idea development through sequenced drawings in time and space. In this cognitive-field partnership (*student + technology + environment*), the OS supports intentional design recursion and production.

The iPhone sketches (Fig 16, p158 middle) abbreviate and truncate, but still mimic Sullivan's lesson from Plate 2 (Fig 15, p157). The app-facilitated drawings depict generative sequencing as a step toward replicating *A System* and its transmittal to mobile technology, in this case to Autodesk's Sketchbook Pro (Coyne 2010. Sullivan 1999. Wolfram 2002). Sullivan's stepped processes, recapitulated in autopoietic recursion and component-assembly, results in

unities and domains that include app layers, my finger gestures, consequent lines, smartphone processing, and Sullivan's instructions as input. *A System* thus becomes research active continuing to influence, stimulate, and guide the development of ideas resulting in drawings that, in turn, generate further potential for design.

This trajectory unfolds *A System's* components and rules as available to code, gesture, and morphological assembly as an illustration of the analog-to-digital influence of *A System* on the autopoietic-extended design construction of metabolic architecture. Following this arc, I associate Sullivan's procedures in a corresponding analogy with Turing's AI, universal machine, and morphogenetic drawings by referencing them to biogenerative L-systems and practices encompassed in tuning (Coyne 2010. Turing 1936. 1952. Wells 2004. 2006). Coyne commented on the paucity of attempts to relate technology and biology — something I attempt to counter with autopoietic-extended design. He wrote:

... the coupling of electronics and organisms point to the fusion of animal and machine. ... Arguably, little attention is granted in the technical literature that celebrates the concerted human labor required in tuning, to successfully connect "biological neural tissue to technology" [Pfeifer & Bongard]. The processes of tuning and such retuning are clearly subject to design consideration (Coyne 2010 67).

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4.2 • *A System* as Evolutionary

In review, I'm plotting a method for learning and researching bioremedial generative architecture envisioned to extend architecture through nature via systems of biology (student), cognition (intelligence), and technology (smartphone/apps). For example, Sullivan's Plate 2 (Fig 15, p157 top two rows) depict fourteen drawing cells in progressive states of evolution, illustrating, as do other drawings, rule-based actions that are sequential in time and space (discrete state), but must be evolved as continuous-state visualizations in order to develop the biological data and form Sullivan intended. These bands of icons relate to geometric pattern/rhythm change and represent animate nature as it is translated in *A System's* teachings Sullivan expected students to follow (Sullivan 1967. 1999).

Setting recursion in motion, *A System* assumes programming adaptivity in its Sullivan assigned lessons, titled:

- 1) Geometric development.
- 2) Manipulation of the organic.
- 3) Manipulation of the inorganic.

- 4) Geometric flow.
- 5) Axial branching.

These five autopoietic-compatible categories label *A Systems'* action potential (rules/categories) and order procedural methods for morphing a drawing from one developmental domain to the next — Sullivan called such evolving actions "impulses" (Sullivan 1979). Maturana and Varela would likely call Sullivan's five categories "topological:"

An autopoietic system is defined as a unity by and through its autopoietic organization. This unity is, thus, a topological unity in the space in which the components have existence as entities that may interact and have relations. For living systems such a space is the physical space (Maturana & Varela 1980 93-94).

Translating Sullivan's animate *impulses* as morphological unities, the drawings are intended to communicate with observers; but, reformulated via autopoiesis brings topological bending, stretching, and expansion I associate with embryological AI/ALife, codes, and algorithms into domains of generative design (Turing 1952. 1953). Through topological manipulations, I situate *A System* side-by-side with Turing's (Chapter 5) decoded botanic drawings and generative computations (Bedau 2003. Richards 2013. Turing 1952. 1953. Wolfram 2002).

Sullivan committed his ideas to pencil drawn and labeled plates on Strathmore paper, but his visionary design processes remain unbounded within the domain of architectural education. As design lessons, the plates were intended to illustrate steps to materialize architectural vision as drawings. But they were also understood as ultimately geared to support realization of building components subsequently in need of carving, molding, and casting. The plates could therefore achieve autopoieticlike extension across domains, materials, and communications.

Used today, *A System* may still be evolved iteratively while maintaining properties of Sullivan's proto-autopoietic process as we engage with it by following his teachings. In following *A System's* drawing domains, we become agents of autopoietic extension as well as vectors of communication enacted by hybridizing and evolving Sullivan's ideas with our own (Clark 2001. Dawkins 1982. Maturana & Varela 1980. Turner 2000). Viewed in this way, *A System's* ideas and procedures continue to replicate.

A System communicates between *Sullivan + designer + pencil + paper* and the domain of students, practitioners, or observers to become an autopoietic-ready subdomain available to enact/engage communication, design, and ideas. According to *Autopoiesis and Cognition*:

... different subsets of relations included in the structure of a given entity, may be abstracted by an observer (or its operational equivalent) as organizations that define different classes of composite unities (Maturana & Varela 1980 xx).

In the organizational communication between the *System* and its users there occurs a metabolic shift from Sullivan's embedded cognitive teaching to the student's cognitive participation and architectural generation. The *System* only engages autopoietically when student/designers bond with it by following and evolving its precepts. From such engagement Sullivan's drawings become agents of their own self-maintenance through the extended cognition of the artist/user/agents (Clark 2001. 2008a). An example of such engagement may be tracked beginning at the left of Plate 2 (Fig 15, p157 third row). The drawing's output, beginning with cell #1 is continuously — autopoietically — active. Each subsequent cell is progressively handed-off to the next for generational elaboration. Cell #12's structure relies on the structure of cells #1-11 — cells #13-14 repeat the same process in two steps.

This cumulative sequence of morphogenetic development, referenced to design output, could be digitally coded. Sullivan and Turing would both recognize the scaling role of Fibonacci numbers when translated as mathematical algorithms and, because of Turing's research (1936. 1948. 1952), *A System* could retrospectively be programmed (e.g. in L-systems) as computable and ALife generative. With growth, development, and communication in mind Sullivan (1999) recognized his process as morphologically ruled and sequential as typified by Plates 2 and 5 (Figs 15, p157. 19, p161) so, without using the terms iterative, emergent, or generative he demonstrated his teaching's recursive processes (Di Paolo 2005. Twombly & Menocal 2000. Varela 1981. Weber & Varela 2002).

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Sullivan never mentions recursion in either *A System* (1990) or in *Kindergarten Chats* (1979), which is curious considering recursion's role in botanic development recognized in his time, domains he studied and referenced Plates 2 and 5 (Figs 15, p157. 19, p161). Nevertheless, his drawing process illustrates autopoieticlike recursion in the finished works as determined by related principles of geometry and non-linear complexity (Bird 2003. Mason 2008a. b). Twombly and Menocal, discussing Sullivan's transformational and generative process, accounts for recursive processes in phrasing such as, "infinite number of times:"

Any shape could turn itself into a decorative motif by generating ornamentation, theoretically of itself. Any item of ornamentation contained, eventually could give birth

to, new motifs, a process that could repeat even an infinite number of times (Twombly & Menocal 2000 157-158).

Often cited to explain cellular automata, Conway's *Game of Life* (Fig 16, p158 bottom) is governed by rules through which game cells computationally live and die. Those rules establish digital birth, survival, and death in:

... a two-dimensional binary cellular automata in which the next state of each lattice cell depends on its own state and sum of the states of its eight immediate neighbors (Beer 2004 4).

Floreano and Mattiussi explain some of the resulting dynamics:

... starting from a random initial configuration reveals the existence of different kinds of "objects." Some correspond to *stable* configurations that remain unchanged from one time step to the next. Conway and his coworkers called these objects *still-life* configurations ... The second kind of common Life objects are *oscillators*, or *life cycles*. These are configurations that repeat themselves with a period greater than one time step ... A third kind of common configuration in Life are *moving objects* ... the simplest and most interesting of them: the *glider* (120-122) ... [Fifteen pages on, Floreano Mattiussi discuss implementing computation in cellular automata] ... when this is possible the cellular system is said to be capable of universal computation. For example it has been shown that this is the case for Conway's Life CA [cellular automata] (Floreano & Mattiussi 2008 137 original emphasis).

Thus, the *Game of Life's* life and death (Chapter 1. 1.7) hinges on environmental rules determined by conditions in neighboring cells (Beer 2004. Emmeche 1994. Floreano & Mattiussi 2008. Gardner 1970. Langton 1988. Wolfram 2002). Discussing maintenance of life and generation of form vis-à-vis the *Game of Life* and computational autopoiesis McMulling & Varela (1997), Varela *et al.* (1974), and Uribe (1981) acknowledged pioneering processes in virtual ecosystems not unrelated to today's advanced simulations of life and intelligence seen, for example, in the OpenWorm (Madrigal 2013) online simulation. This virtual organism (Fig 21, p183) simulates a nematode's metabolic and physiological states in what I see as a de facto model of an advanced CAD delineated biogenerative architecture (OpenWorm.org 2013) whose ancestors began life in the *Game of Life*.

By writing *A System's* rules directly onto his drawing sheets, Sullivan embedded his voice, narrative, and intention into his drawn visualization (Hayles 1999. Sullivan 1999). He stressed phenomenological "impulses" (Sullivan 1967. 1979) compatible with his form's production in what I link to AI, ALife, or genetic algorithms. *A System* reads as a set of teaching rules visually and textually coding actions Sullivan considered desirable and important to design education. Below I sample Sullivan's phenomenological narrative in what today we might label emergence:

The creative reality of form lies within a continuous series emanating from a single primal life-impulse seeking and finding manifold expression in form. Life itself is thus manifested in a constant flow into countless multitudes of specific forms (Sullivan 1967 Plate 7).

If we read "continuous" as *recursive*, "life-impulse" as *metabolic*, and "manifold expression" as *generative*, Sullivan's subjective phrases may be extended through time and technology and evolved autopoietically in ways similar to those I extend from *Wasp and Pear* (Chapter 2. 2.2) and deploy in autopoietic-extended design.

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Sullivan sought to embed graphic accounts of living plants colonizing geometric matrices resembling trellises. He depicted stylized botanic form and movement overlaying patterned shapes, associating architectural ornament with communicating dynamic urban and democratic life by means of biological nature he envisioned for his building facades (Paul 1962. Sullivan 1961. 1979). His intention — architecture as communication — was operational, supported by his belief that his drawings, once translated into façade panels, communicated meaning to observers, while his buildings' scale and structure — Chicago School cage frame as organic matrix (Sullivan 1896) — compounded the drawings' generative meaning (Sullivan 1979 140). *A System* encapsulates his final attempt at teaching this vision-in-practice for architecture, its lessons, both ornamental and transcendental, however did not come at an auspicious time for their reception. Modernism rendered ornament outdated, a "disease" according to Adolf Loos's manifesto, *Ornament and Crime*: "the evolution of culture is synonymous with the removal of ornament from utilitarian objects" (Loos 1908 20).

Using Plates 2 and 5 (Figs 15, p157. 19, p161) as representative of *A System's* instructions, I return to their graphic development. Along with Sullivan's term "impulse," the drawings demonstrate generative actions involving vision, thought, and design. The generative drive in his systemization of rules descends in what today is categorized as non-linear dynamics

and complexity, leading to emergence supplemented by creative vision, his phenomenological "impulse" (Bird 2003. de Duve 2002. Johnson 2001. Menocal 1981. Paul 1962. Sullivan 1967. Twombly & Menocal 2000).

Turing (1950) considered a different generative approach. He too concerned himself with the observation of plants (Allaerts 2003. Dollens 2014. Hodges 1983. Saunders 1992. Swinton 2004. 2013), but he interpreted their biological functions, not for aesthetic or transcendental generation, but for writing code where morphological properties might reveal clues to intelligence (Allaerts 2003. Saunders 1992). Sullivan, in contrast, concerned himself with symbolic and transcendent processing whereby forms conducted visual meaning from the architect's thinking via drawings to expression on buildings for reading and decoding by the person on the street (Menocal 1981. Sullivan 1979. 1999).

Sullivan's draftsmanship embedded ideas key to his visualizations of forms in nature. I'm not attempting here to decode those transcendent implantations in aesthetic terms or to poetically decode any specific building ornament (Menocal 1981. Paul 1962). But, I would like to establish their relationship as communication devices and stress that their impact carried over in The Wainwright Building, The Guarantee Building, and The Bayard Building for example, and more closely related to *A System*, in the highly ornamented late bank buildings (Fig 20, p162) (Weingarden 1984). In terms of material translation, Sullivan's expression of organic growth over geometric frames was realized through the mediums of exterior cast-terra cotta, various interior and exterior metal castings, and complexly colored decorative interior stencils such as those in the Chicago Stock Exchange Trading Room (Vinci 1977).

Sullivan began each drawing (Sullivan 1967. 1999), and presumably each building, with rudimentary lines drawn according to morphological rules intended to propagate the lines' development in subsequent steps (Sullivan 1896. 1999). But, he considered properties and attributes of lines within a phenomenological frame larger than pencil marks. His goal-oriented and teleological drawings contributed to the communication process he associated with architecture in *A System* (Sullivan 1979. 1999). Discussing "variations or combinations," he opened a domain of processing rules suited to algorithmic articulation; on Plate 5 (Fig 19, p161) he wrote:

Any line, straight or curved, may be considered an axis, and therefore a container of energy . . . there is no limit to variations or combinations, or to the morphology possible. . . . Axes may be expanded, restrained, combined, subdivided, made rigid or plastic, or mobile, or fluent in every conceivable way. They may be developed inorganically or

organically; they may be developed as stolid, or as filled with the life-impulse (Sullivan 1967 Plate 5 Fig 19, p161).

Menocal, referring to Sullivan's strategy:

There is a botanical analogy here also. Any line in ornamental design may be compared with a young stem which in due time shoots out leaves, and although it may eventually disappear from view and even memory beneath the foliage, the branch remains always in the controlling axis of the design. . . . Plates 5 [Fig 19, p161] and 6 of the *System* show how a designer has the power of liberating the aesthetic energy lying hidden within the confines of lines and geometric shapes, and of determining whether this release will create new geometric axes or new vegetal motifs (Menocal 1981 31).

Taken as Sullivan's manifesto, *A System's* coded and generative lines, "constitute the simple working idea upon which all that follows is based — as to efflorescence." (Sullivan 1967 Frontispiece). Efflorescence, French "to flower out" (Wikipedia 2014m), opens *A System* with an iconlike drawing of a germinating dicotyledon seed. The seed, throughout Sullivan's work, philosophically whispers: ideas grow akin to seeds. Sherman Paul traces Sullivan's thinking to Taine's 1875 "The Philosophy Art" from *Lectures on Art*, noting that Sullivan "learned from Taine that genius and talent were normal endowments — 'gifts like seeds'" (Paul 1962 4). One-hundred-and-twenty-three pages later Paul categorizes *A System* as the "more remarkable" book when compared to Sullivan's *Autobiography of an Idea*:

Not only does it [*A System*] most succinctly state Sullivan's basic ideas, it also visualizes them. It is a treatise on man, on the act of creation as the ripest fulfillment of his powers . . . [where] 'nothing is really inorganic to the creative will . . .'

The source of this vital power is the ego, the unity of all man's physical, mental, emotional, moral, and spiritual powers. It is comparable to the germ of the seed which is the 'seat of identity' and which contains the 'will to live,' the pressure which ever seeks its full expression in form. *A System of Architectural Ornament* shows the seed seeking its form in efflorescence (Paul 1962 127-128).

Within *A System*, recursive lines express energy and creativity (Plate 5 Fig 19, p161); inspired by the germination of a seed, they metaphorically root biological and phenomenological growth that I interpret through autopoietic-extended design as mathematical, narrative, and

graphic communication. Backed by logical rules, the drawings foretell systemization and integration with the architectural expression and unity for which Sullivan's earlier buildings were known (Weingarden 1987. Twombly & Menocal 2000).

Coincidental here, the metaphor of an idea-as-a-seed-as-an-efflorescing-idea traces back to Taine's (Paul 1962) published lectures. But the 1875 book also contains Sullivan's likely exposure to:

... a work of art is determined by an aggregate which is the general state of the mind and surrounding circumstances (Taine 1875 87).

If correlated with current extended cognition looking to mind and environment (Clark 2008a), Taine's quotation provides embryonic background for "form ever follows function" as including the function of the generating mind in a living environment. Sullivan in this light is generative, the architect credited with coining "form ever follows function" (Sullivan 1979 170) — later abbreviated to "form follows function." As circulated in Modernist times, the logical premise (or cliché) became an article of design faith, slenderized in a mantra, and not unrelated to Le Corbusier's (2007) "a house is a machine for living in" (Chapter 2. 2.1) and more recently to Gosden's (2010) "the house is an intelligent object" (Chapter 6. 6.1).

When user engaged, *A System* is autopoietic and reproductive, capable of inspiring new work. The book is organizationally communicative and domain defining as it attempts to, in Maturana and Varela's words,

... continually regenerate and realize the network of processes (relations) that produced [it] (Maturana & Varela 1980 79).

Potentially, *A System* generates more drawings when someone uses it. Therefore, by attracting and enlisting users — not only viewers — Sullivan provided a mechanism for future production capable of collaborative self-maintenance with adaptation and variation (Di Paolo 2005. Varela 1981. Weber & Varela 2002).

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4.3 • A System Updates

If all the villas Palladio did not design, but that can be extrapolated from his drawings and built works, are algorithmically generated in *Possible Palladian Villas*, why shouldn't *A System's* morphology be analyzed, autopoietically charged, and computed in the same manner? (Hersey & Freedman 1992). Beyond the still viable potential surrounding generative grammars (Alexander

et al. 1968. 1977. Chomsky 1959. Lindenmayer 1968), *Possible Palladian Villas* reveal intent to generate neohistoric digital structures, thereby adding liminal revival typologies to research investigation. The sampling of historical styles, illustrated by Hersey and Freedman's book, relates to morphological form generation, though not the impact or outcome developed via biology, technology, and autopoietic-extended design though *A System*.

Whereas a priori rules must be assigned to Palladio's forms in order to result in generative expression, students' exploration of nature can synthesize the process, challenging their research to extract and decode natural systems in order to apply experientially observed rules to architectural performance. This process demonstrated in Turing's botanic and embryological coding and simulations (Chapter 5) conveys style, form, and patterning into algorithmic code as well as into potential metabolic performance (Saunders 1992. Turing 1952. 1953).

Greg Lynn, looking to environmental, morphological, and metabolic process to interpret and decode site conditions and to program form responses in software, developed strategies for projects published in *Folds, Bodies, & Blogs* (1998), *Animate Form* (1999) and *Predator* (2006). For example, he used landscape data and weather patterns to create rules for, as well as restrictions on, shape formation and applied the parameters as guides for computational generation (Lynn 1999 142-163). Autopoietic-extended design guides related methods for generating design from nature's data through contemporary theory and technology in order to investigate environmental functions and natural forces useful to metabolic building systems.

More in tune with current generative design than the digital Palladio projects, but more formally restricted than *Animate Form*, is Andrew Heumann's (2013) Tweet2Form (Fig 22, p184). His app, attuned to social-media domains, is in a generative sense related to Sullivan, Turing, and design m-learning as an architectural *system* Twitterbot (Heumann 2013. Wolfram 2002 938). Starting with a basic geometric shape, Tweet2Form's code is applied as a shape generator coded by the user's Tweeted script written from a simple rule-set programmed by Heumann (2013).

Like the *Game of Life* and *A System*, Tweet2Form applies rules in linear, sequential commands for generative output. Heumann noted in an email that his intention "emerged out of an interest in self-diagramming algorithmic processes — the idea that an algorithm can build a graphical representation of its own procedures" (Heumann 2013a). But unlike the *Game of Life* or *A System*, Tweet2Form's morphological generation evolves "graphical representation[s]" as axonometric drawings. A user compiles a coded Twitter message with Heumann's script by arranging its command vocabulary; for example, "fold shearA stretch scale twist split bridge bend shearD shearD stretch stretch stretch split bridge" (Heumann 2013). The preceding code

corresponds to a Tweet2Form message I sent (Fig 22, p184). As a design tool, Tweet2Form illustrates the way an architectural app may be envisioned for on-the-fly generation, recursion, and variation in smartphones with in-field design response.

Schematically, Sullivan's *System* is a meditation on design and learning in need of, and open to, cognitive and/or algorithmic extension. If we hypothetically imagine *A System* as programmed akin to Tweet2Form, we could then expand Sullivan's rules, program, and methodology in order to differently visualize his pedagogy redeployed for smartphones and apps (Heumann 2013. Prusinkiewicz & Lindenmayer 1990. Wolfram 2002).

The resulting analog/digital drawings, STL models, or class programs communicate between students (agents) and nature via extended cognition and technology where cognition morphs ideas for architecture as adaptive responses to data entering realms for the production of extended phenotypes (Dawkins 1982. Hansell 2005. Turner 2000). My hypothesis illustrates how current design learning might be inspired to source nature using theory and technology for class procedures as well as for app implementation where, in Varela *et al.*'s (1991) words "the notion of coupling [joining, grouping, communicating] with an environment is conceptualized."

I suggest that Sullivan's aim of an input-output morphological synthesis of nature, rule-sets, and drawing stands in common with Turing's biosimulations of patterns from fircones, sunflowers, and radiolarians (Richards 2013. Turing 1953). Sullivan intended student implementation of *A System*'s nature-mimicking performance; Turing (1936) conceptualized a computational system that by the 1940s and 1950s was vital to further visualize digital simulation and programming that still grounds computation (*Nature* 2012. Prigogine & Nicolis 1967. Sullivan 1979). Sullivan was explicit about hybridization, leaving instructions that the student or designer:

... may substitute in thought [their] own will as the seat of vital power [e.g. the seed] in a figuratively or imagined. . . . energy-base of a theory of efflorescence (Sullivan 1967 unpaginated).

From those words I metaphorically consider *A System* as proto-machinic (Chapter 1. 1.3), available to autopoietic-extended design integration (Deleuze & Guattari 1987. Maturana & Varela 1980. Parr 2010. Raunig 2010). In respect to Turing, I reflect on *A System*'s pedagogical sequencing, icons, and stepped instructions as capable of being coded. Thereafter, the *System*'s morphological processing opens to shells, bones, diatoms, radiolarians, etc. as generative domains Sullivan occupied with plants for architectural communication and physical functions. In so doing, *A System* self-references itself, testifying to the situation whereby Sullivan's physical

buildings become metadata and another level of communication for envisioning urban environmental data, pattern, and function (Sullivan 1990). Toward that testimonial, I loop Sullivan's words concerning inert materials as elements of life and communication:

So the materials of a building are but the elements of earth removed from the matrix of nature, and reorganized and reshaped by force; by force mechanical, muscular, mental, emotional, moral, and spiritual (Sullivan 1979 32).

Sullivan's buildings translated his phased visualization into architectural expression, communication, and function. His constructed work points out how two-dimensional drawings come uncannily close to his three-dimensional, solid architectural ornament. Sullivan's channel of production flowed through phases in which artists carved prototypes from which they made molds in order to cast metals or terra cotta panels and building blocks. Such *Visualization-to-craft*, and *visualization-to-materialization* may subsequently have been lost owing to expense, changing taste, and lack of production knowhow.

Today however, computation, machine production, and material science (Gershenfeld 2012. 2014) make possible a resurgence of craftsmanlike detail via digital fabrication. In architecture for example, Herzog and de Meuron's buildings in which patterning, material research, digital fabrication, and, sometimes, ornament are integrated through design theory, research, and machining (Ursprung 2002). For enacted living technology, 3D medical printing is currently producing human bladders and working toward printing kidneys for human transplantation (Atala 2011). This is science and technology with prototyping lessons appropriate to metabolic generative architecture and should be theorized and extrapolated from for new learning and design research potential (Atala 2011. Moon 2014).

Computer-numerically-controlled (CNC) fabrication and rapid prototyping via stereolithography (STL), in the context of architect-, engineer-, and scientist-driven investigation come into play for autopoietic-extended design as part of its program to manifest biological and digital simulation. The synthesis is achieved through student's deployment of autopoietic-extended design protocols that access technology and nature as resources for thinking as well as living technology and, eventually, bioprinting (Atala 2011. Fountain 2013. Gershenfeld 2012). That process allows contemplation of hybridizing AI, biorobotics, and living technology for biological and ecological materials incorporating metabolic agents (Fountain 2013). Carole Collet's *Studies in Material Thinking* paper, positions such research where:

... living technology can foster a new approach to address some of the key sustainable

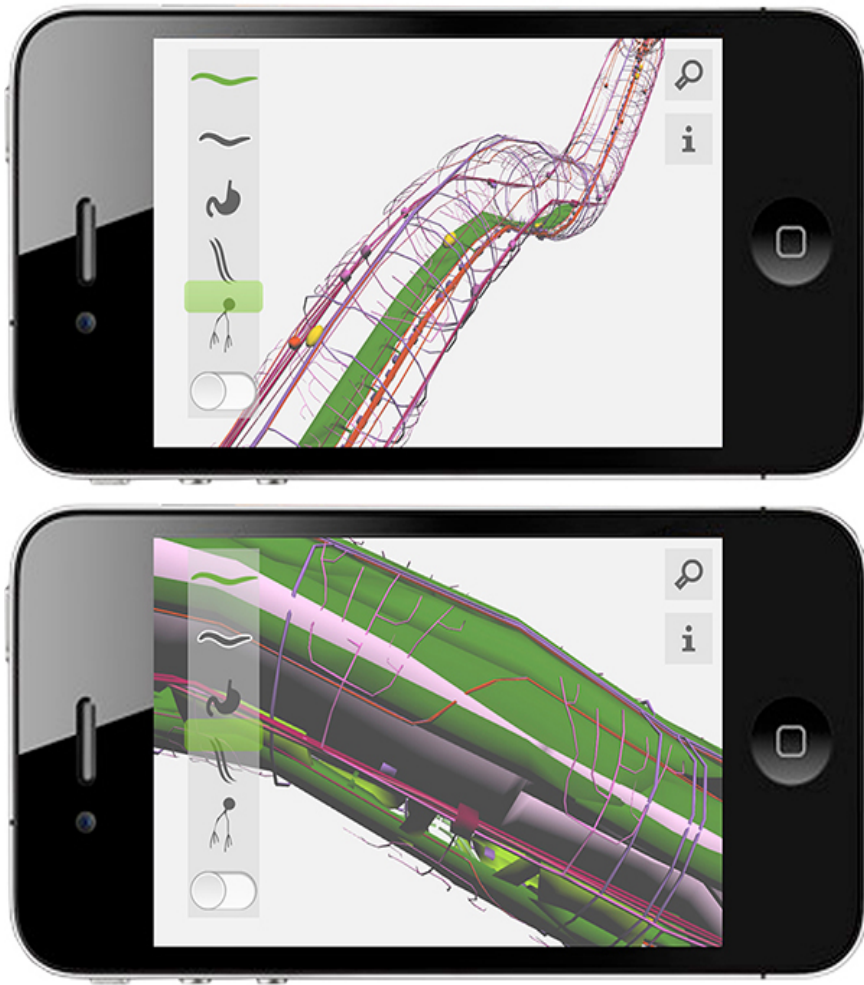


Fig 21. OpenWorm.org iOS App. Used in autopoietic-extended design class discussions as a digital-autopoietic model facilitating architectural investigation into metabolism, morphology, organization, and biodigital collaborations conducted over the Internet. The visual and morphological relationship here between an architectural infrastructure and digital ALife is relevant to this thesis when discussions of life and intelligence become part of a buildings environmental and bioremedial functions. Images: Dennis Dollens.



Fig 22. Right: Screen shot of Andrew Heumann's Tweet2Form architectural generator. Left: Four Tweets using Heumann's code, generate four returned Tweets with generative forms. Dennis Dollens: Tweets to Tweet2Form, 20 December 2012.

challenges of the 21st century. . . . [T]o probe the potential of a biological manufacturing future by exploring the cellular programming of morphogenesis in plant systems (Collet 2012).

The emerging potential of synthetic life, living technology, and computation accordingly reinvents materialization when it is considered as metabolic, and when it prevents, again in Sullivan's (1979 32) words, "elements of earth [from being] removed from the matrix of nature." Neil Gershenfeld and J.P Vasseur support a view of new synthesis compatible with that process:

The Internet's defining attribute is its interoperability, information can cross geographical and technical boundaries. With the Internet of Things, it can now leap out of the desktop and data center [and laboratory and mobile studio] and merge with the rest of the world (Gershenfeld & Vasseur 2014).

Sullivan affirms plant morphological change driving *A System's* operational procedures and communication. Annotating *A System's* drawings, he fused ideas for hybridizing botany with his transcendental narrative (Menocal 1970). The resulting *System* testifies to his belief that the architect's vision, derived from geometry and animated by biological life, "can cross," in Gershenfeld & Vasseur's words, "geographical and technical boundaries." Sullivan insisted:

It cannot for a moment be doubted that an art work to be alive, to awaken us to its life, to inspire us sooner or later with its purpose, must indeed be animate with a soul (Sullivan 1979 194).

The significance of *A System* today lies not in whether or not a building has a soul but in whether it has intelligence. The significance of *A System* therefore lies in the integration — its interoperability — of nature, communication, and teaching without discriminating dualisms separating the architect and architecture from nature (Canguilhem 1992. Gibson 1986). For autopoietic-extended design, *A System* affirms a role for morphological/metabolic visualization communicating through an autopoietically sourced, extended cognitive network for bioremedial generative architecture.

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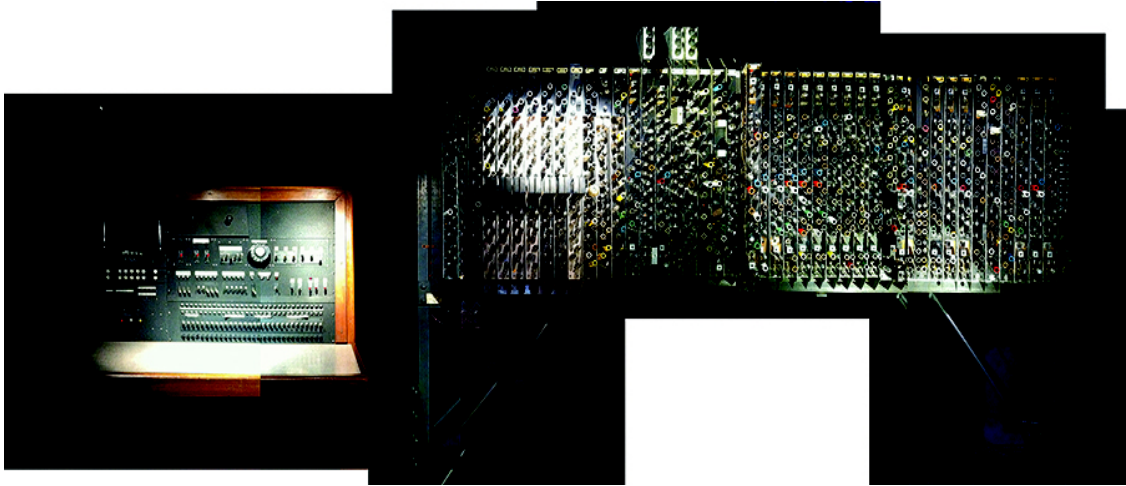


Fig 23. One of the few existing landmarks related to the origin of computational biology and botany. Pilot Automatic Computing Engine (Pilot ACE), 1950. Exhibited as part of "Code Breaker: Alan Turing's Life and Legacy." 21 June 2012 – 31 July 2013. Science Museum, London. Turing worked on the design of the earlier, larger ACE, but left the National Physical Laboratory (NPL) before the pilot was built. David Rooney notes Turing: "wrote one of the first practical designs for a stored-program computer, later realized as the 'Pilot ACE'" (Rooney 2012). The Science Museum exhibition material stated that the Pilot ACE is: "The most significant Turing artifact in existence" (Rooney 2012). Photograph & collage: © 2012 Dennis Dollens.

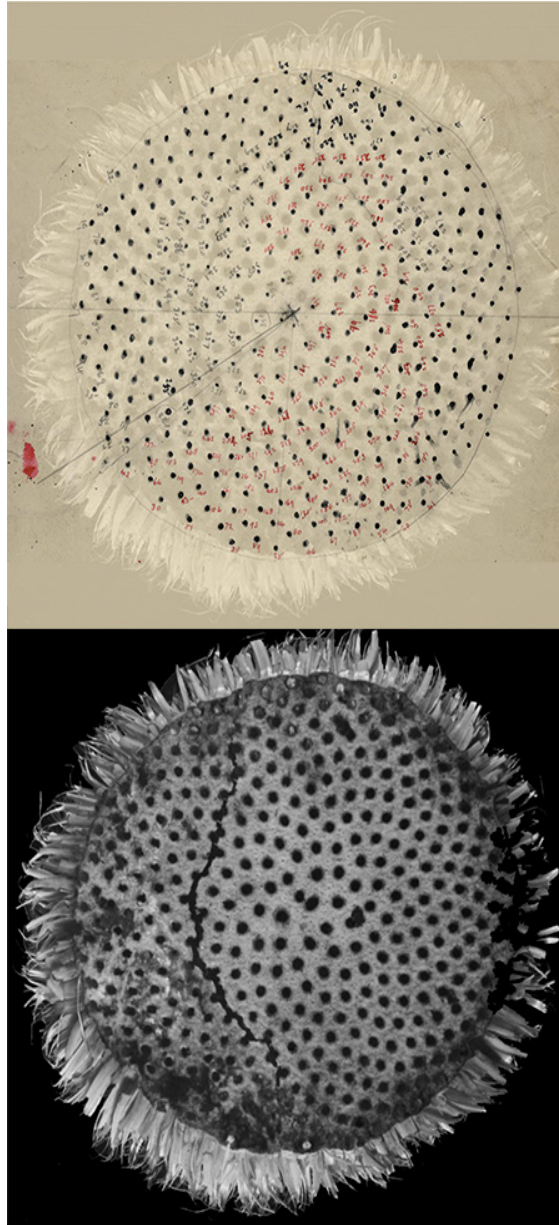


Fig 24. Superimposition of Turing's *Helianthus* phyllotaxis drawing onto the photograph (bottom) he used to position its growth sequences delineating Fibonacci spirals.
 Graphic: ©Dennis Dollens. Photograph: Turing Digital Archive, AMT/C/25 Image 96. Courtesy: © P.N. Furbank. Drawing: Turing Digital Archive, AMT/C/25 Image 95. With permission: © P.N. Furbank.

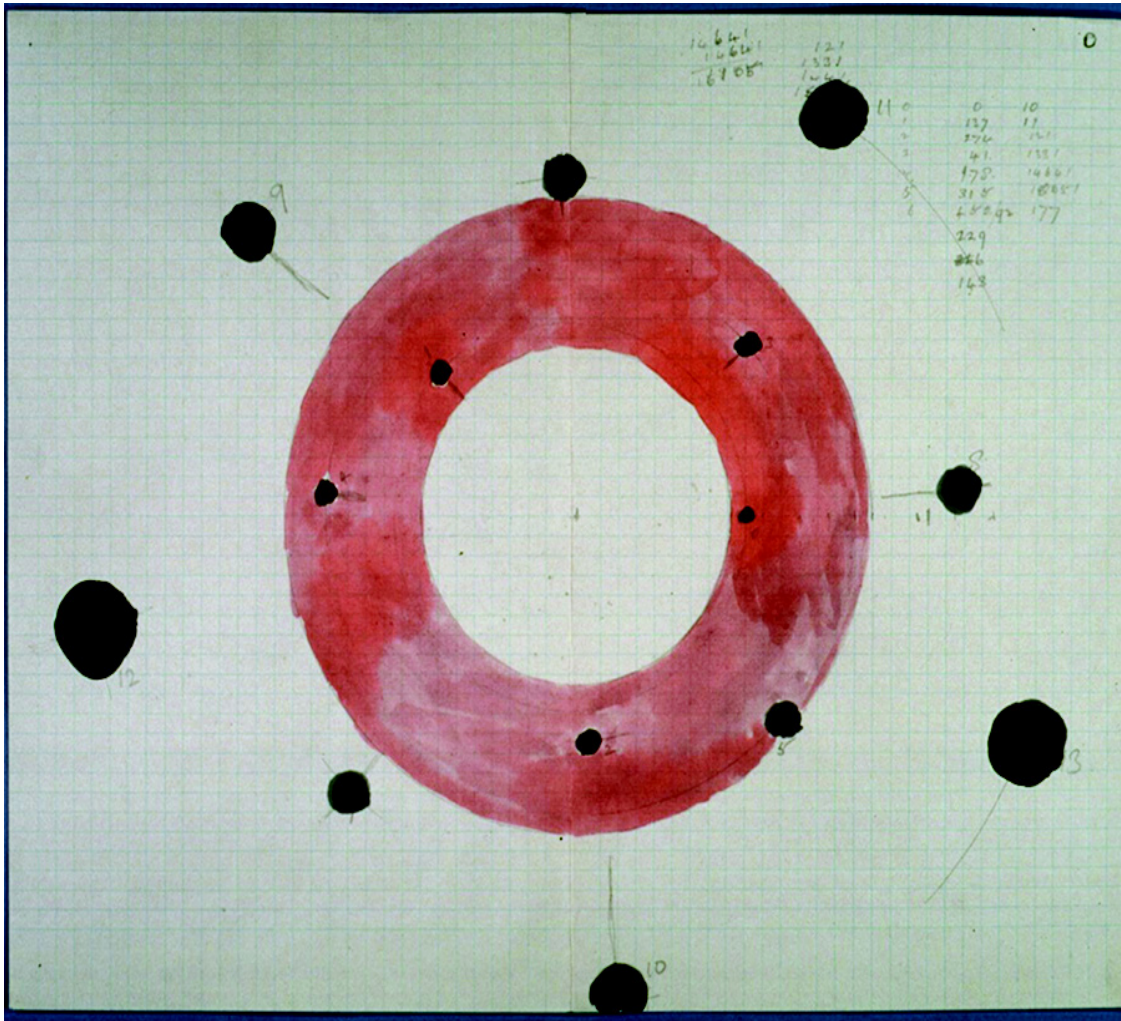


Fig 25. Alan Turing. Drawing. An Idealized Flower Bud Formation, following a counter-clockwise Fibonacci spiral calculated from the 3 o'clock position of the innermost spot and then spiraling at 137°. Jonathan Swinton has calculated and annotated this drawing (Swinton in Cooper & van Leeuwen 2013 837). Drawing: Turing Digital Archive, AMT/K3/3. With permission: © P.N. Furbank.

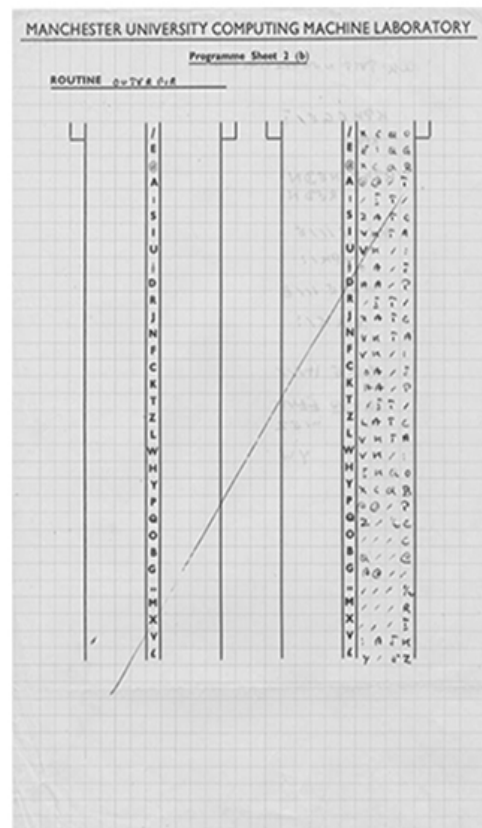
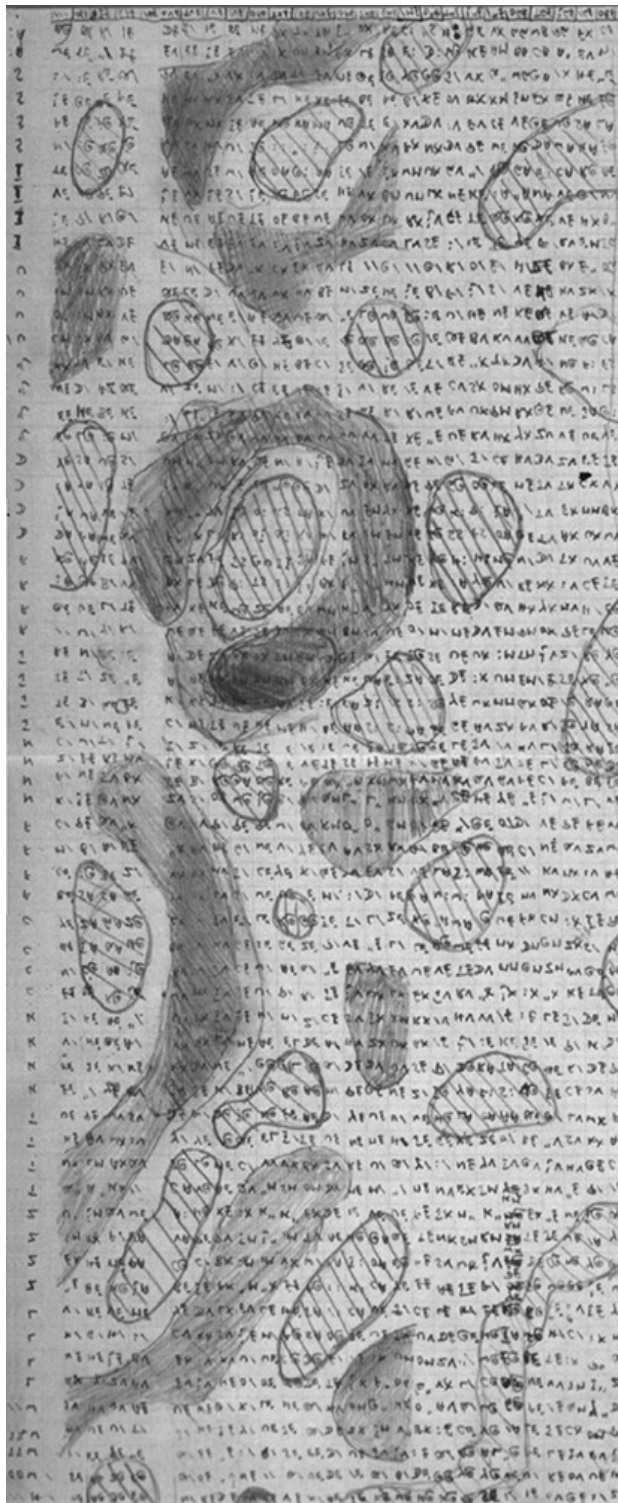


Fig 26. Left: Alan Turing. Computer Simulation. Turing's reaction-diffusion drawing illustrating pattern distribution and formation. The generative background's computational matrix was hand transferred from a computer printout to delineate the foreground pattern by code. Drawing: Turing Digital Archive, AMT/K3/7. With permission: © P.N. Furbank. Right: Alan Turing. Manchester University Computing Machine Laboratory; Programme Sheet 3(b). Programming in Turing's hand titled "OUTERFIR," discussed by Hodges (1992 494) as a computer routine associated with fircone investigations. Outerfir is not programming for the image on the left but is typical of Turing's coding sheets. Turing Digital Archive, AMT/C/27. Image 042. With permission: © P.N. Furbank.

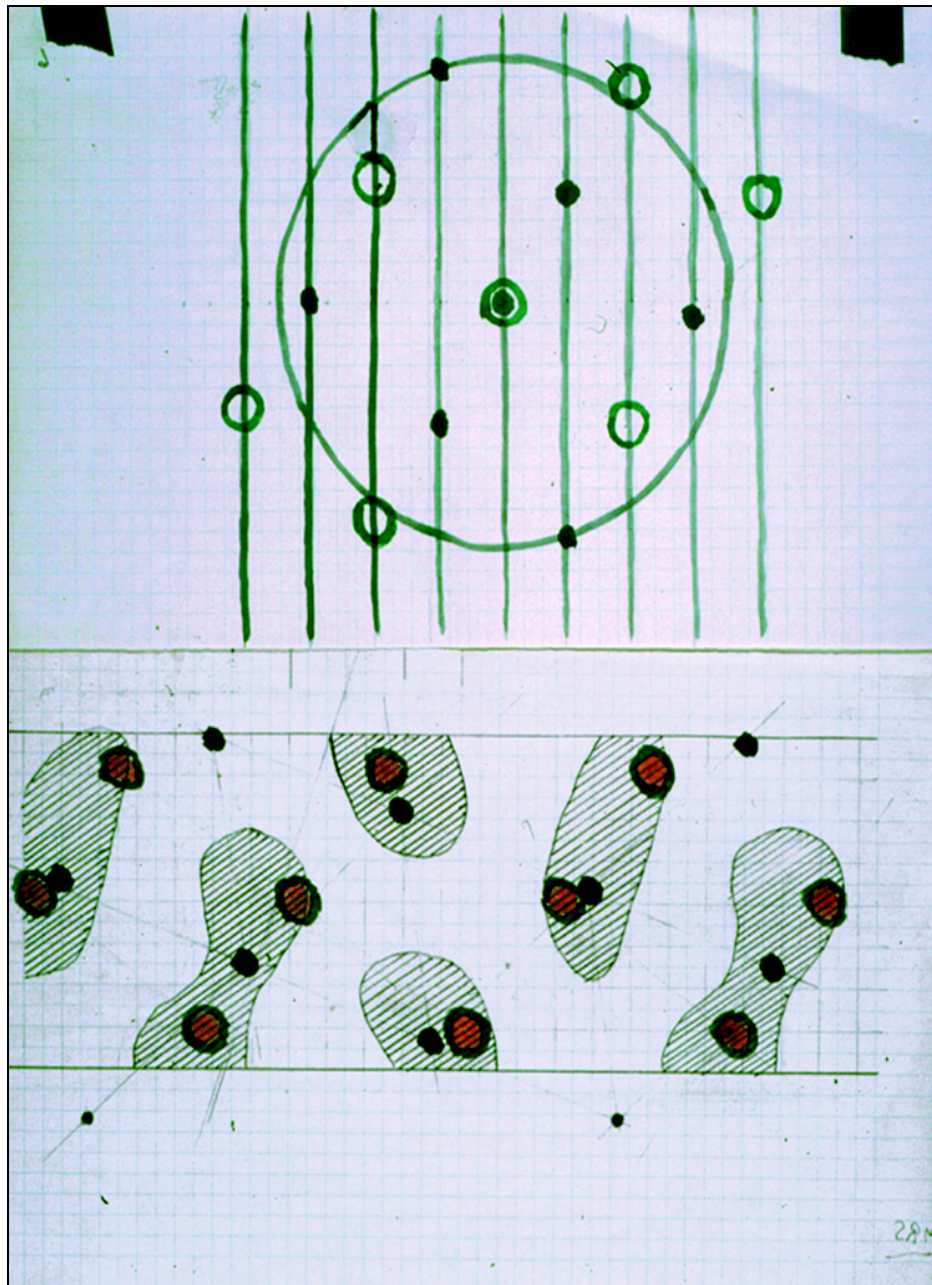


Fig 27. Alan Turing. The top drawing depicts a parastichy (spiral) pattern generatively relating to the lattice below, where the hatched, cellularlike forms express the system's patterning. (See: Swinton in Cooper & van Leeuwen 2013 841). Drawing: Turing Digital Archive, AMT/K/3 Image 6. With permission: © P.N. Furbank.

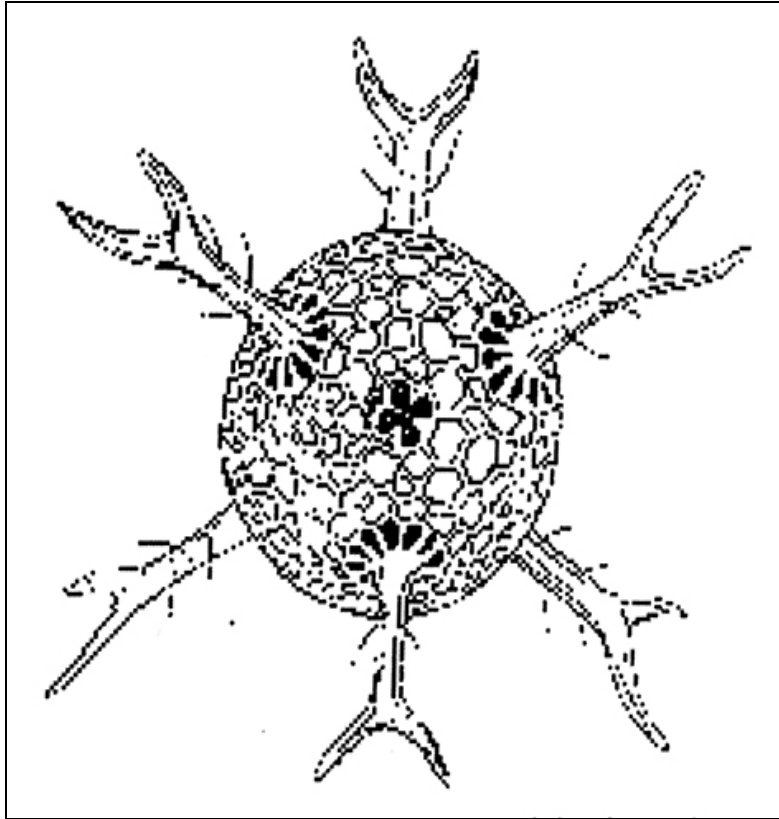


Fig 28. Morphogenetic Digital Simulation. Circa: 1954.
From Bernard Richards's (2005) "Turing, Richards and Morphogenesis" generated after Turing's death but predicated on his morphogenetic equations recalculated and programmed by Richards for his MSc thesis. With permission: The Rutherford Journal: The New Zealand Journal for the History and Philosophy of Sciences and Technology.

Chapter 5 • Alan Turing: Simulating Nature

Asking *Can buildings think?* implies an underlying question, *can buildings metabolize?* Both reference work Alan Turing (1950) undertook in: "Computing Machinery and Intelligence," while simultaneously depending on his definition of a universal computer theorized in: "On Computable Numbers, With an Application to Entscheidungsproblem" (Turing 1936). Thereafter, if architecture is contemplated as metabolic, both *Can buildings think?* and *Can buildings metabolize?* theoretically intertwine biology and computing with building performance (Brenner 2012. Reinitz 2012). My journey through such questions thus opens conceptual pathways explored by Turing here considered for application in generative architecture.

If Turing, the WWII codebreaker (Copeland 2012. Dyson 2012. Hodges 1992), saw nature as code bearing, holding processes useful to machine intelligence, he may have rooted certain strains of his morphogenetic research in biocomputation plotted through direct observation of nature (Saunders 1992. Wells 2004). John Reinitz, writing in *Nature* in 2012 tells us:

In "The Chemical Basis of Morphogenesis," Turing [1952] showed that a pattern can indeed form *de novo*. In considering how an embryo's development unfolds instant by instant from its molecular and mechanical state, Turing was using a modern approach. Developmental biologists today similarly investigate how molecular determinates and forces exerted by cells control embryonic patterning. . . . [Turing] created a nonlinear system by turning on diffusion discontinuously in an otherwise linear system . . . (Reinitz 2012 464 original emphasis).

And, Reinitz connects the patterning to computation, first stating:

The influence of Turing's paper is difficult to overstate. It was a transition point from the era of analytical mathematics to that of computational mathematics. . . . Turing's paper contains the first computer simulation of pattern formation . . . and is possibly the first openly published case of computational experimentation (Reinitz 2012 464).

Nobel Prize laureate, Sidney Brenner came to a similar conclusion:

"The Chemical Basis of Morphogenesis" explored the hypothesis that patterns are generated in plants and animals by "chemical substances called morphogens, reacting together and diffusing through a tissue." Using differential equations Turing set out how instabilities in a homogeneous medium could produce wave patterns that might account for the processes

such as the segregation of tissue types in the developing embryo (Brenner 2012 461).

In a more general frame involving botany as focused upon here, Hodges speaks of Turing's morphogenetic project:

... he had his hands on another central problem of life, this time not of the mind, but of the body, although both questions were related to the brain. ... he had always enjoyed examining plants when on his walks and runs, and now he began a more serious collection of wild flowers from the Cheshire countryside, looking them up in his battered *British Flora*, pressing them into scrapbooks, marking their locations in large scale maps, and making measurements. The natural world was overflowing with examples of pattern; it was like codebreaking, with millions of messages waiting to be decrypted. Like codebreaking, the field was open-ended; with his chemical model he had one sharp tool to apply to it, but that was only beginning (Hodges 1992 434 original emphasis).

I look to four drawings (Figs 24-27, pp188-191) Turing produced by hand or programmed in computers and transferred to paper; and one (Fig 28, p192) produced after his death by Bernard Richards (Dollens 2014. Richards 2005. Swinton 2004. 2013. Turing Digital Archive 2014). My intention is to connect his drawings, statements, archival notes, and experiments by situating them as starting points of generative design. Turing's study of nature is well documented (Copeland 2012. Hodges 1992. Swinton 2004. 2013. Turing 2012), and his schoolboy familiarity and lifelong use of mathematical biologist, D'Arcy Thompson's *On Growth and Form*, is considered important because in Turing's time that book was alone in the field of mathematical morphology (Hodges 1992. Saunders 1992. Thompson 1992/1917. Turing 1952. Turing 2012). More significant, *On Growth and Form* helped Turing formulate experiments: "intended to defeat the argument from design" (Saunders 1992 XII). Working toward that end, Saunders tells us in the *Collected Works of Alan Turing: Morphogenesis*:

For Turing, however, the fundamental problem of biology had always been to account for pattern and form (1992 XI) ... Turing, who had been very much influenced by D'Arcy Thompson, set out to put [his] program into practice. Instead of asking why a certain arrangement of leaves is especially advantageous to a plant, he tried to show that it was a natural consequence of the process by which the leaves are produced. He did not in fact achieve his immediate aim ... On the other hand, the reaction-diffusion model has been applied to many other problems of pattern and form (Saunders 1992 XII).

To this subject, Copeland found: "Turing took his cue from . . . D'Arcy Thompson to whom he refers at the end of ["The Chemical Basis of Morphogenesis"]" (Copeland 2004 508). And, Przemyslaw Prusinkiewicz connects Thompson to Turing in, "Visual Models of Morphogenesis" (Prusinkiewicz 1994). There, Prusinkiewicz writes, Turing's computer "simulation results . . . has led to a better understanding of morphogenesis and given rise to new procedural techniques for realistic image synthesis." He continues:

Historically, the study of morphogenesis has been approached from two directions. The first one consists of viewing form as a derivative of growth and was formulated by D'Arcy Thompson: "It is obvious that the form of an organism is determined by its rate of growth in various directions; hence rate of growth deserves to be studied as a necessary preliminary to the theoretical study of form."

The second direction focuses on the flow of substances [reaction-diffusion] through a medium and was initiated by Turing: "The systems considered consist of masses of tissues which are not growing, but within which certain substances are reacting chemically, and through which they are diffusing. These substances are called morphogens, the word being intended to convey the idea of form producer" (Prusinkiewicz 1994 62 quoting Thompson 1992/1917 and Turing 1952). (See quotation pp210-211: Prigogine & Nicolis 1967).

Richard Dawkins wrote acknowledging Thompson's place in biology. From *The Extended Phenotype* (Dawkins 1982), I jump to Turing's observed and programmed "transformational" nature realized as algorithmic depictions of plant movement. Dawkins's reasoning parallels that of Prusinkiewicz and Turing for ongoing consultations with *On Growth and Form's* ideas of morphological development.

D'Arcy Thompson's (1992/1917) celebrated chapter "On the theory of transformations" . . . is widely regarded as a work of importance. . . . We go back and look at animals [plants for Turing] in a new way; and we think about theoretical problems, in this case those of embryology and phylogeny and their interrelations, in a new way (Dawkins 1982 2).

To incorporate Dawkins's line of thinking and support it with Turing's use of *On Growth and Form*, I look to a contemporary view from architectural scholarship. This view from Michael Weinstock's "Self-Organization and Material Constructions," aligns with the above quotations and expresses an appreciation of Thompson's research as it affects current generative design:

D'Arcy Thompson discussed the mathematical expressions of the shapes of growing cells in 1917, arguing that new biological structures arise because of the mathematical and physical properties of living matter. His chapter on "The Forms of Cells," when read in conjunction with the "Theory of Transformations," has been extended today to [reaction-diffusion] patterning and differentiation in plant morphogenesis (Weinstock 2006b 35).

Taking cues from *On Growth and Form's* publication as a chronological marker for mathematical morphology — seven years before Sullivan's *A System* — I surveyed related historic methods, ideas, and technologies for landmarks in the development of generative architecture (Lynn 1998. 1999. 2006). *On Growth and Form* and *A System* were published close enough in time to for me to double anchor them as forerunners to computational architecture (Lynn 1999. Sullivan 1999. Thompson 1992/1917. Turing 1952). Opening with Thompson, and continuing through the present day, I sketch a lineage in which Turing's drawings speak to developments in digital simulation and algorithmic design and therefore to ongoing research (Deussen & Lintermann 2010. Floreano & Mattiussi 2008. Prusinkiewicz & Lindenmayer 1990. Prusinkiewicz 1994).

IBM's SyNapse chips (2011), Stanford/Venter's computational bacterium (Covert *et al.* 2012), and Adamatzky's (2013) slime mold are my contemporary counterpoints. The Stanford/Venter simulated bacterium living in 128 computers (Covert *et al.* 2012. Markoff 2012. Venter 2013), IBM's learning SyNapse chips released in 2014 as "Neurosynaptic System⁴¹⁴: TrueNorth" (Markoff 2014. Merolla *et al.* 2014), and Adamatzky's (2013) living technology (amoeba) follow possibilities seeded and embedded, though far from conceptualized in Turing's "Intelligent Machinery" (1948), "Computing Machinery and Intelligence" (1950), "The Chemical Basis of Morphogenesis" (1952), and "Morphogen Theory of Phyllotaxis" (1953).

I suggest this lineage be viewed as the historic foundation for generative architecture, acknowledging Turing's role in morphological nature-to-computation drawings and their role in today's algorithmic processing and simulation. What this lineage establishes is fourfold:

- 1) Turing's hand drawing, computer simulations, and programming, considered in light of generative architecture, initiated and demonstrated intellectual and technological research manifested in biodigital simulation, digital animation, and biological coding now available in programming languages and software such as L-systems.
- 2) Turing's ideas for visualizing and digitally translating nature — nature's algorithmic computability — is pioneering and thus important for AI, ALife, generative architecture,

digital biomimetics, computer graphics, environmental simulation, and machine/cognition prediction.

3) Turing's 1950s methodology — observational/computational — holds insight for teaching ways of looking at nature for morphological and biomimetic data and technology and integrating it with design, computational generation, and visualization for architecture learning, research, and practice.

4) Turing's (1953) calculations for embryological development and morphological simulation of radiolarians, demonstrated (Fig 28, 192) by Richards (2013/1954) after Turing's death, launches digital, 3D-form generation of biological life.

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5.1 • Building Intelligence

Alan Turing's "Intelligent Machinery" (1948) was a theoretical projection of future-possible computation with eventual implications for AI, synthetic biology, biomimetic design, scripted architecture, and fabrication-by-code. It was followed, two years later, by the question: "Can machines think?" published in "Computing Machinery and Intelligence" (1950). Possibilities have since been growing from those two papers. "Can machines think?" was concurrently given biological importance underscored in Turing's (1952) on-going morphogenetic plant explorations and their relationships with computers (Copeland 2004. Dyson 2012. Prigogine & Nicolis 1967. Prusinkiewicz 1994. Richards 2012. Swinton 2004. 2013. Turing 1950. 1952. 1953).

Yet, while Turing's overall research impacted general computing, cellular automata, cybernetics, AI, and ALife — the exact intentions of his morphogenetic experiments, in relation to digital simulation, gradient control, switching, prediction, theories of mind, and computation still hold mysteries (Bedau 2003. Copeland 2012. Hayles 1999. Hodges 1992. Swinton 2004. 2013. Turing 1953).

Unknown or little considered, Turing's research drawings are eye opening for pedagogical approaches to visualize design morphology, algorithmic botany, architectural biomimetics, and generative design (Figs 24-27, pp188-191). And while his late research papers (Turing 1948. 1950. 1952. 1953) had direct impact on, for example, Aristid Lindenmayer's (1968. 1971. 1975) development of a biological programming language known as L-systems (Deussen & Lintermann 2010. Hensel 2006. Prusinkiewicz & Lindenmayer 1990. Veen & Lindenmayer 1977), Turing's biological studies and drawings were only published and discussed much later (Allaerts 2003. Dollens 2014. Lindenmayer 1968. Prigogine & Nicolis 1967. Richards 2013. Saunders 1992. Swinton 2004. 2013). Today, and in the context of generative architecture, we hear Achim Menges on morphogenesis playing an increasingly important role in advanced systems and materialization:

Natural morphogenesis, the process of evolutionary development and growth, generates polymorphic systems that obtain their complex organization and shape from the interaction of system-intrinsic material capacities and external environmental influences and forces. . . . [This] approach to architectural design entails unfolding morphological complexity and performative capacity from material constituents without differentiating between formation and materialization processes. . . . [T]he core of such a morphogenetic approach is an understanding of material systems not as derivatives of standardized building systems and elements facilitating the construction of pre-established design schemes, but rather as generative drivers in the design process (Menges 2006 79).

In a BBC Radio *Third Program* broadcast, Turing (1951) defined two points that set the stage I use to read his drawings, in Menges's words as "generative drivers." First, and for a general audience, he clarified his 1936 theoretical construction, the universal machine:

A digital computer is a universal machine in the sense that it can be made to replace any machine of a certain very wide class. It will not replace a bulldozer or a steam-engine or a telescope, but it will replace any rival design of calculating machine, that is to say any machine into which one can feed data and which will later print out results (Turing 1951 2).

Turing's second point recalls the Turing Test — originally the "imitation game" (Turing 1950) — where computers respond to human questions to determine if machines can be considered intelligent. His BBC transcript continues:

One does not need to be able to understand how these orders [codes, programs] lead to the machine's subsequent behavior, anymore than one needs to understand the mechanism of germination when one puts a seed in the ground. The plant comes up whether one understands or not. If we give the machine a program which results in its doing something interesting which we had not anticipated I should be inclined to say that the machine *had* originated something, rather than to claim that its behavior was implicit in the program, and therefore that the originality lies entirely with us? (Turing 1951 6 original emphasis).

Importantly, as Donald Michie (a friend and former Turing student) tells us:

[T]he question which Turing wished to place beyond reasonable dispute was not whether a machine might think at the level of an intelligent human. His proposal was for a test of whether a machine could be said to think at all (Michie 2002 29).

By questioning concepts of metabolism, machine, and code intelligence, Turing hunted biologically related processes distributed in nature and reproducible in technology that foreshadowed intelligent machine speciation and ALife (Copeland & Proudfoot 2004. Langton 1988. Montebelli *et al.* 2013). In his quest for observational clues to physiological and chemical movement in plants, Turing's morphogenetic searching could be related today to biomimetics (Ball 2001. Benyus 1997. *Nature* 2012). First though, to visualize a universal Turing machine, this beautiful Lego model built by Jeroen van den Bos and Davy Landman (2012) shows a working model in a 2.22-minute video (<https://www.youtube.com/watch?v=FTSAiF9AHN4>). From here we need a conceptual framework for understanding how, according to Wells: "the concept of the abstract computing machine that now bears his name" (Wells 2002 160) impacts generative architecture? Toward an answer, Benjamin Woolley writes:

... a computer that could compute any computable number does not sound like the most shattering intellectual advance. But that is because we got used to the idea of the computer. In 1936, it meant a person. Following Turing's insight, it meant a machine: he had proved, in other words, that it was possible to mechanize what had previously only been possible by means of mental effort. The machine had crossed a critical barrier. Before, machines had taken over the body, now they threatened to take over the mind. . . Turing's insight, however did much more than just establish the limits of mechanical calculation. It introduced the idea of the universal machine, a machine that can be lots of different machines; in fact, a machine capable of being any machine capable of performing a computation (Woolley 1992 222-223)

Holding Woolly's comments in mind while thinking of Turing's BBC commentary, we find the Turing machine viewed from Copeland and Proudfoot with reference to its function, context, and impact:

Turing introduced his "universal computing machine" and the idea essential to the modern computer — the concept of controlling a computing machine's operations by means of a program of coded instructions stored in the machine's memory. This work

had profound influence on the development in the 1940s of the electronic stored-program digital computer . . .

The universal computing machine of 1936 — now known simply as the "universal Turing machine" . . . consists of a scanner and a limitless memory-tape that moves back and forward past the scanner. The scanner reads the symbols on the tape and writes further symbols. The machine has a small repertoire of basic operations; complexity of operation is achieved by chaining together basic operations (Copeland & Proudfoot 2004 317).

Andrew Wells (2002) reads Turing's 1936 paper with an environmental interpretation. He lists five perceptual or environmental functions, translating between machinic and metabolic terms he calls, "perceptual and motor systems" (2002 164). The five points charted, provide insight into tasks Turing may have resolved years later through plant drawings (Fig 25, p189) calculated for algorithmic expression (Swinton 2004. 2013. Wells 2002. Wolfram 2002) hinting that his morphogenetic papers (Turing 1952. 1953) carried over ideas, functions, and implications planted in his 1936 universal machine (Allaerts 2003. Dollens 2014. Swinton 2004. 2013). In a surprise, the interpretation Wells developed (2004. 2006) posits a "universal *environmental* machine" compatible with such lengthy theory and algorithmic gestation; especially considering that Turing's morphogenetic research embedded concepts important to both machine intelligence and biological simulation (Brenner 2012. Reinitz 2012). Wells proposes the universal environmental machine where:

- 1) . . . perceptual systems allow . . . [the universal machine] to scan a single square of the tape at a given time and to recognize that it is blank or that it contains one of the symbols. . . [where]
- 2) . . . motor systems allow it to erase the symbol on the scanned square, to print a symbol, and to move one square to the left or right so as to change the scanned square. [Where]
- 3) . . . environment . . . consists of a one-dimensional tape divided into squares . . . [where]
- 4) time . . . is divided into a series of discrete moments . . . which are such that exactly one instruction is carried out in each moment. [And, where the]
- 5) . . . key notion is succession rather than duration (Wells 2002 164).

With its functions so outlined, Wells offers a new interpretation of Turing's work as the "universal *environmental* machine." This reading provides a continuum between Turing's later biological/morphological research to root with his early theory of computing and schematically integrate the machine as part of the environment where:

- 1) Perception = Scanning. 2) Motor systems = functional erasing, printing, and moving.
- 3) Environment = paper tape, machine components, and ambient surroundings. 4) Time = duration of one action. 5) Key notion = succession not duration.

Perception, motor system, environment, time, and key notion recognizes in Turing's (1936) theory an integrative accounting of cognition and environment where even the virtual machine is reliant and responsive to algorithmic changes directing different programming criteria to machine behavior. This includes theoretical implications for biological computation and, eventually, autopoiesis (Maturana & Varela 1980) and extended cognition (Clark 2008a). The universal environmental machine's conceptual implications for my thesis, is that Wells's interpretation of intelligence and environment (embedded in Turing's proposition) is compatible with Clark and Chalmers's (1998) *parity principle*, Gibson's *affordances* (1986), as well as with Maturana and Varela's (1980) autopoietic *structural coupling*. Wells identifies a plausible reading of Turing's universal machine accounting for eventual distributed environmental input and shared cognition. From his reformulation I factor in metabolic environments, machine thinking, and programming that enable prediction in ways Clark (2013a) currently describes (Di Paolo 2005. Wells 2002. 2004. 2006).

Herein, the contemporary expression of a thinking machine may not need to be expressed in traditionally understood terms of a universal Turing machine, but rather in the frame of a *universal environmental machinic*, and Wells's insight may be the foundation. Intelligence and metabolic functions are currently on the agendas of research labs around the world, taking in fields such as synthetic biology, living technologies, and biorobotics (Garrett 2013. Bedau *et al.* 2010). Slime mold, to name one organism (Barnett 2014), is currently being considered at the University of the West of England, Bristol for roles in micro processing chips (Adamatzky 2013). As an example of biology interfacing electronics, Adamatzky's research previews computational directions science and technology are now pushing biosynthetic and computation hybrids (Garrett 2013). This is, in a real sense harvesting and deploying intelligence in nature paralleling what we see in, for example, the new silicon chip from IBM modeled on the brain's neural networks; in IBM's case with "one million 'neurons' about as complex as the brain of a bee" (Markoff 2014).

One related science/technology crossing point I find important for architecture education and research is in alerting students to, and involving them in, the evolution and cultivation that technology, ALife, and biomaterial developments will likely implement for design over the course of their careers. From that perspective, I remix Turing's morphological and algorithmic research holding onto his question: "Can machines think?" (Turing 1950). As the question is reprocessed by new generations of students, it needs to branch and flower differently so that architecture is reclassified as machinic, making germane: Can buildings think? (Turing 1936. 1948. 1950. 1952. Wells 2002. 2004. 2006). One avenue leading toward an answer to this question is to define alternative metabolic intelligence, and one fork in that direction is emerging in plant neurobiology (Brenner *et al.* 2006. Gagliano *et al.* 2014. Mancuso 2010. Pollan 2013).

Retrospectively, and without direct reference, Maturana and Varela augment my investigation of Turing's search for computational morphogenesis (Maturana & Varela 1980. Turing 1950. 1951. 1952). While Turing's work was mathematical, Maturana and Varela's tackled biology, questioning how to define minimal life systems in their theory of autopoiesis (Maturana & Varela 1980. Varela 1979). Moreover, with Ricardo Uribe they began experimental computation to program cellular autopoiesis as a digitally living, genetic algorithm (McMulling & Varela 1997. Uribe 1981. Varela *et al.* 1974. Wolfram 2002).

On a computational note: Maturana, Varela, and Uribe were able to draw upon theory developed and matured when they programmed autopoiesis as a digitally living cellular automata demonstrating self-maintenance, reproduction, and death (McMulling & Varela 1997. Uribe 1981. Varela *et al.* 1974). For perspective, the three scientists knew Conway's *Game of Life* (Emmeche 1994. Gardner 1970. Varela 1979) and may have known Lindenmayer's (1968. 1971) computational mathematical biology.

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5.2 • Machinic Phylum & Phenotypes

By questioning what is necessary for minimal life, Maturana and Varela's *Autopoiesis: The Organization of the Living*, frames theory pertinent to cognitive processes concerning nature and technology. In turn, that process helps establish a lineage of generative architecture when it supports research methods extended through design and learning. Such an extension draws from differently engaged historical feedback than exists in current design education because autopoietic-extended design is based on a premise recognizing architecture as part of technology, and technology as part of nature — both only understood through cognitive construction of reality as species determined (Clark 2008a. 2013a. Lettvin *et al.* 1959. Turing 1952. Wells 1998. 2002. 2004. 2006).

Since machines and buildings exist in a phylum of human construction (built artifacts to serve human functions or desire), we logically may ask of a building what we ask of a machine. Therefore Turing's question, "Can machines think?" (1950) synonymously resonates in, "Can buildings think?" because machine/building similarities are correspondingly recursive in terms of energy feedback and data input/output, they are both tools.

That feedback (Hayles 1999) is then channeled environmentally, technologically, or cognitively as operationally adaptive in student's metabolically active and cognitively extended design conceptualizations. In this dynamic context, I consider Turing's (1951 6) statement as phenotypically prophetic: "I should be inclined to say that the machine had originated something" (Clark 2008a 123. Dawkins 1982. Hansell 2005). In those words we find Turing's narrative, although predating Maturana and Varela's (1980) theory and cellular automata (Varela *et al.* 1974), aiding an evolutionary line of enquiry when Maturana and Varela ask, why shouldn't living machines be constructed? I then view their cellular automaton (Uribe 1981. Varela *et al.* 1974. Varela 1979) in light of their words below, as historically assisting the construction of metabolic architecture today:

Machines are generally viewed as human made artifacts with completely known deterministic properties which make them, at least conceptually, perfectly predictable. Contrariwise, living systems are a priori frequently viewed as autonomous, ultimately unpredictable systems, with purposeful behavior similar to ours. If living systems were machines, they could be made by man and, according to the view mentioned above, it seems unbelievable that man could manufacture a living system. This view can be easily disqualified, because it either implies the belief that living systems cannot be understood because they are too complex for our meager intellect and will remain so, or that the principles which generate them are intrinsically unknowable; either implication would have to be accepted a priori without proper demonstration. There seems to be an intimate fear that the awe with respect to life and the living world disappear if a living system could be not only reproduced, but designed by man. This is nonsense. The beauty of life is not a gift of its inaccessibility to our understanding (Maturana & Varela 1980 83).

Complementing Maturana and Varela's argument for buildable living systems, Langton wrote:

Artificial Life is the study of man-made systems that exhibit behaviors characteristic of natural living systems. It complements the traditional biological sciences concerned

with the *analysis* of living organisms by attempting to *synthesize* lifelike behaviors with computers and other artificial media. By extending the empirical foundation upon which biology is based *beyond* the carbon-chain life that has evolved on Earth, Artificial Life can contribute to theoretical biology by locating *life-as-we-know-it* with the larger picture of *life-as-it-could-be* (Langton 1988 original emphasis).

Today, machines typified by smartphone functionality, imbued with sensor perception and AI systems, are examples for architecture of Turinglike machine intelligence capable of assisting and evolving generative design (Dennett 1998. Langton 1988). Smartphones and apps are massively distributed and exemplify human-to-machine cognitive collaboration. I see their design, materials, fabrication, and coding as models of current technology for architectural domains. I repeat, Turing's "I should be inclined to say that the machine had originated something" (Turing 1951 6) as insightful when a smartphone's sensors and Google AI deliver unexpected data assisting memory and feedback — all the more so if "originated something" refers to constructing information (Luhmann 2000) as environmental attributes ordering *materialization* and *spatialization* through design.

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Fibonacci series describe proportional mathematic sequences encompassing parametric scale, spiraling, and pattern growth (Thompson 1992/1917). From ancient times such numeric progressions were thought to represent nature's harmonics. Biological growth sequences (phyllotaxis and parastichy in relation to Turing) often follow computable geometric ratios. Through such sequencing we see that Fibonacci or Golden Section proportions have played leading roles in mathematical and morphological studies (Thompson 1992/1917. Sullivan 1999. Swinton 2004. Turing 1953).

Turing (1953) opens "Morphogen Theory of Phyllotaxis" by considering chemical mechanisms for the metabolic placement of leaves, seeds, bracts, spots, petals, markings, or branches in patterned formations (Swinton 2004. 2013). Defining phyllotaxis Hensel notes:

Phyllotaxis (Greek *phyllo*: leaf + *taxis*: arrangement) is the study of the arrangement of repeated plant units and the pattern of their repetition within the same alignment. These include leaves arranged around a stem, scales on a cone or pineapple, florets in the head of a daisy, and seeds in a sunflower. Spiral phyllotaxis is a phyllotactic pattern where the elements are arranged as a spiral lattice . . . (Hensel 2006 15).

Jonathan Swinton logs in with:

Phyllotaxis means here the arrangement of structures, such as leaves or florets in plants. To see the phenomenon of Fibonacci phyllotaxis, consider the arrangement of side branches on the main stems of a plant. . . . A remarkable fact . . . is that . . . it exhibits a number of parastichy [spiral] pairs, each of these pairs consists of two adjacent Fibonacci numbers from the sequence 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, . . . in which each number is the sum of the preceding two. . . . [R]emarkable is that this property can be found in very many examples in many different species of plants. Explaining this ubiquity is the problem of Fibonacci phyllotaxis (Swinton 2004).

Turing's drawings from this period, translated into graphics (sometimes computer assisted), simulate metabolic plant actions — biochemically switched on spiraling patterns or growth ratios (Figs 24-27, pp188-191). Turing was, Wilfried Allaerts (2003) observes: "eager to unveil the mathematical foundations of living, biological organization." And, in unveiling living, biological organization Turing, like Maturana and Varela (1980) after him, sought to understand life systems. In Copeland's opinion: "Turing was the earliest pioneer of computer-based A-Life: he was the first to use computer simulation to investigate a theory of the development of organization and pattern in living things" (Copeland 2004 508).

In retrospect, the challenge for morphogenetic research to decode and digitally simulate biological development now appears to resemble aspects of 1930s and 1940s code breaking challenges via mathematics and machine deciphering (Copeland 2012. Copeland & Proudfoot 2004. Swinton 2004. 2013. Turing 1950. 1952). Hensel suggests attuned logic for architectural research following suit:

When attempting to set forth a paradigm for differentiated and multi-performance architectures, it is interesting to examine available methods for modeling biological growth informed by a hosting environment. Through this investigation it is possible to derive architectural strategies and methods that are informed by environmentally specific conditions and, thus, to achieve advanced levels of functionality and performativity (Hensel 2006 13).

Turing attempted to decode biology like he decoded WWII messages, through direct observation and pattern variations while using computation, prediction, and machine power (Copeland 2012. Dollens 2014. Hodges 1992). The endeavor is relevant considering Turing's interest in machine potential, human thought processes, and subsequent coding used years later

in design, simulation, and animation (Lindenmayer 1968. Prigogine & Nicolis 1967). Turing's question, "Can machines think?" (1950) is seminal, as are the two question opening this paper: Can buildings think? and Can buildings metabolize? Herein, Maturana and Varela's argument for the eventual construction of human-built living machines (1980 83) enriches Turing's query.

For generative design, resonance from "Can machines think?" is significant when considering the machine(s) Turing designed and those he later had access to at Manchester. Throughout much of the 1940s, he was designing the Advanced Computing Engine (ACE) at the National Physical Laboratory (NPL), leaving only after being sidelined and frustrated (Fig 23, p187) (Copeland 2012 141. Hodges 1992. Rooney 2012). In September 1948 he joined Manchester University to participate in its rapidly evolving machine design and building program (Copeland 2004. Hodges 1992. Napper 1999). Hodges notes: "He had conceived of a universal machine, and now he could work or play with one of the two that existed in the world" (Hodges 1992 408).

Suggestively, the time frame of Turing's drawings coincides with some of the Manchester's most advanced machines. We know that in early 1951 he was awaiting a new machine, the Ferranti Mark I, for calculations involving fircone phyllotaxis and chemical embryology (Turing 1951b) and, that undated programming in his hand for fircone computation exists in the Turing Digital Archive (Fig 26, p190 right). Brian Napper (1999) writes that after 1951 Turing was "a keen user of the computer [Ferranti Mark I] as a tool for his research interests, which turned to 'morphogenesis.'" Viewing the Mark I in the role of biological computation and simulation may then allow us to envision the world's first commercially available, general-purpose computer producing the world's first biodigital graphics — on screen and via teleprinter (Fig 26, p190 left) (Copeland 2013. Reinitz 2012. Swinton 2004. 2013).

For researchers today, clues from Turing's letters, papers, and drawings point to digitally generative methodologies that find 1950s expression in machine-generated data. Such clues assist decoding Turing's process as digital biomimetic observation. Turing writes in the "Morphogen Theory of Phyllotaxis:"

Phyllotaxis deals with the arrangements of leaves on the stems of plants. By a liberal interpretation of the terms "leaf" and "stem" it deals also with the arrangements of florets [Fig 24, 188] in the head (e.g. in a sunflower) and with the leaf primordial near the growing point of a bud. All these kinds of patterns will be discussed. . . . [T]he leaves are usually treated as if they were geometrical points distributed on a cylinder. Such patterns on cylinders [parastichy] are appropriate for the description of the mature structures, but their use may be criticized on the grounds that the patterns of real

importance are not those formed by the mature structures, but [rather] on the leaf primordia. I would indeed go further and say that we should not consider even the primordia but certain patterns of concentration of chemical substances ("morphogens") which are present before there is any visible growth of primordial at all. . . . consideration of the patterns formed by the mature structure is enormously helpful (Turing 1953 49).

When I look at Alan Turing's drawings of Fibonacci phyllotaxis and reaction-diffusion patterns (Figs 24-27, 188-191), I find them bridging technology and his pioneering interest in mind, AI, and ALife (Brenner 2012. Copeland & Proudfoot 2004. Hodges 1992. Reinitz 2012. Teuscher 2004a). As working drawings they computationally reiterate questions people have asked of nature, pattern, and rhythm for thousands of years. Cultural and scientific curiosities such as the drawings are often then first usefully categorized as cognitive extensions (2008a xxv). But additionally, the drawings are mathematically, computationally, and machine related, suggesting a documentary route by which Wells's (2004. 2006) "universal *environmental machines*" could arrive at an autopoietic unity of *intelligence + machine + nature*.

Explanatory pattern mathematics date back to 6th-century Indian mathematics introduced to Europe in 1202 by Fibonacci's *Liber Abaci* (Wikipedia 2013d). I contend that Fibonacci-type decoding, digitally instrumentalized by Turing's — flower-to-mathematics-to-code-to-computer output (Figs 24-25, pp188-189) — may be considered as a digital-biomimetic observation method viable for students. Then, student nature-to-drawing or prototype productions should be cultivated and extrapolated through generative design methods used in autopoietic-extended design's pedagogical tool chest (Appendix 1).

Turing's drawings then operate pedagogically. They depict the decoding of nature for communication feedback loops while establishing a basic vision of analog-to-digital generative simulation. (Copeland 2013. Dollens 2014. Swinton 2004. 2013. Turing 1950. 1951. 1952. 1953). The drawings thereby inform procedural development and methods for design research, at the same time they anchor biogenerative architecture's computational origin.

As synthetic biology and algorithmic simulation mature in forms deployed by generative architecture, our view of Turing's interest in AI, plants, pattern recognition, and reaction-diffusion can be more easily unfolded. We see not only Turing's work heralding digital graphics and computational simulation but also foreshadowing biological, environmental, technological, and cognitive interconnectedness between cognition, nature, and machines. Related to biochemistry, embryology, and thus to thinking, biological *morphogens* (Turing 1952) and

biochemical reactions are today still open for investigation (Brenner 2012. Reinitz 2012). Swinton, discussing reaction-diffusion in relation to Turing instability, gives an overview:

Turing [1952] provided a hypothesis to explain the generation of pattern when [a] smooth sheet of cells develop pattern during development in a wide variety of settings including the formation of leaf buds, florets, skin markings, and limbs. According to this hypothesis, chemicals called morphogens generate organs when present in sufficient density, and the pattern is created through mechanisms of reaction and diffusion (Swinton 2004)

Sidney Brenner opened his 2012 editorial in *Nature* with: "Biological research is in crisis, and in Alan Turing's work there is much to guide us" (Brenner 2012); while John Reinitz elaborated in the same issue:

At the heart of pattern-making is symmetry-breaking. Turing considered an idealized embryo beginning with a uniform concentration of morphogens, which have translational symmetry that is lost as specific tissues emerge. He raised deep questions that are still unsolved, noting for instance that all physical laws known at the time had mirror-image symmetry, but biological systems did not. Turing speculated that the asymmetry of organisms originated from that of biological molecules. His point is still relevant to life's origins.

Turing's argument involved a mathematical trick: he created a nonlinear system by turning on diffusion discontinuously in an otherwise linear system at a specific instant. Without diffusion, the system is stable and homogeneous, but with diffusion, it becomes unstable and forms spatial pattern (Reinitz 2012 464).

Turing himself wrote, that morphogen:

... is not intended to have any very exact meaning, but is simply the kind of substance concerned in this theory ... [as] evocators diffusing into a tissue somehow persuade it to develop along different lines [switching] from those which would have been followed in its absence (Turing 1952 38 in Saunders 1992 2).

Here I read, "develop along different lines" from Turing above, and before that Reinitz's "turning on diffusion," as inducing change or more clearly as switched or switching — in

Prigogine and Nicolis's (1967 3543) terms "phase transition[s]." If I reductively analyze, "evocators diffusing into a tissue somehow persuade it to develop along different lines" (Turing 1952), I again arrive at a generalized description of switching. Switching, phased or abrupt, is a primary mechanical action universal machines (and cognition) need to produce computation, to change states, communicate, and to write to memory. I speculate the above description of "morphogen" can be more fully interpreted for computational and machine functions if we read it as part of Turing's search for biological switching and phase-transition performance models suitable for incorporation into machine code (Turing 1952). After all, one of his primary insights into modern computing (Turing 1936) was *switching* a machine's program not altering its physical configuration as was standard at the time (Dennett 1998. Dyson 2012. Copeland 2012). In this frame, for this thesis, transposing "Can machines think?" into "Can buildings think?" requires cognition-to-environmental switching to arrive at systems parity (Clark 2008a) and/or structural coupling (Maturana & Varela 1980) in order for architectural sense-making to engage.

Jonathan Swinton located Turing's reaction-diffusion drawing (Fig 26, p190) among the first visualizations of botanic computation (Swinton 2004 490. 2013). And, a year earlier, Wilfred Allaerts noted Turing's:

... endeavor branched off to extend the 'computable' to the realm of biological organisms. ... Turing sought an explanation of how a chemical soup of molecules in an embryo could possibly give rise to a biological pattern (Allaerts 2003).

B. Jack Copeland and Diane Proudfoot considered Turing's interest in biological patterns and AI and contend:

The central aim of Artificial Life is a theoretical understanding of naturally occurring biological life — in particular of the most conspicuous features of living matter, its ability to self-organize. ... Turing was the first to use computer simulation to investigate a theory of ... pattern in living things (Copeland & Proudfoot 2004 335).

Allaerts arrived at a compatible conclusion in the Belgium Journal of Zoology:

Turing is very confident [in 1951] that his work on reaction-diffusion theory will make clear "what restrictions are really implicated" [Turing K/1, Nr. 78] (to the development of brain structure), and announces that he is interested in J.Z. Young's remarks on the simulation under certain circumstances of neuron growth. ... On another occasion

[1950], when comparing the activities of the human mind and the analytical properties of digital computers . . . Turing argues that digital computatory algorithms and human intelligence can be completely matched or considered as perfect imitations of each other (Allaerts 2003).

Turing's "The Chemical Basis of Morphogenesis" is still referred to as pioneering; Philip Maini (2004) said "Turing's work has inspired huge amounts of mathematical biology;" and, "The Chemical Basis of Morphogenesis" paper was discussed by Meinhardt as holding:

. . . the very important discovery that spatial concentration patterns can be formed if two substances with different diffusion rates react with each other. This is entirely contrary to our intuition since with diffusion one associates a smoothing of any local accumulations of molecules but not the creation of such concentration maxima. . . . The connection of this type of reaction with irreversible thermodynamics has been worked out by Prigogine and Nicolis (Meinhardt 1982 8) (Culminating in a Nobel Prize for Prigogine).

Crediting and discussing Turing's "most remarkable paper" to the extent of carrying over variables and quoting equations, Prigogine and Nicolis (1967) note "'The Chemical Basis of Morphogenesis,' has given examples of unstable homogeneous situations in chemically reacting autocatalytic systems." They proceeded to then "give a short summary of Turing's mechanism and . . . show that near thermodynamic equilibrium the steady state satisfies the requirements of linear nonequilibrium thermodynamics." Prigogine and Nicolis deduced in 1967 that they had proven "the existence of a symmetry-breaking instability for the Turing mechanism, in situations sufficiently far from thermodynamic equilibrium." Remarkable here, in relation to symmetry and biological-computational simulation was the question of how a symmetrical embryo develops asymmetrically (Turing 1951a). They speculate,

Even on a broader scale, it is difficult to avoid feeling that such instabilities should play an essential role in biological processes and especially in the first biogenetic steps. It is indeed clear that biological structures can only originate in a dissipative medium and be maintained by a continuous supply of energy. Now the instability we have studied proves precisely such a link between organization and dissipation. . . . chemical instabilities appears therefore to us to be of great interest and may perhaps some day

lead to a better understanding of the processes responsible for the origin of life (Prigogine & Nicolis 1967).

While proof of algorithmic simulations, intentions for AI, and computer-graphic priority is illusive and obscured by Turing's suicide, the evolving nature of scholarly research, as Swinton (2004), Copeland (2012), Allaerts (2003), and Meinhardt (1982) attest, is relevant to machine visualization and intelligence.

A further obstruction to understanding Turing's contributions to coding, programming, simulation, and computer design was the extraordinarily long security sequestration of information concerning his role in British secret intelligence surrounding Colossus, the Bombe, Enigma, and programming at Bletchley Park during World War II (Copeland 2012. Hodges 1992). In this context, Turing's morphogenetic theory, drawings, and graphic computer studies — all translating coded natural data, seem aberrant and distanced from projects such as the Turing Test or the universal computer. That aberration is frequently considered a reason for the bipolar view existing between biologists primarily knowing Turing for reaction-diffusion and for those in information sciences not knowing much about his computer design and programming (Copeland 2012. Dyson 2012a. Hodges 1992).

Yet Turing's theory and drawings were essential steps in computational biology and simulation linking his research programs through older achievements and toward new potential (Reinitz 2012). And those steps have had subsequent impact on computational simulation (Lindenmayer 1968. 1971. Lindenmayer & Prusinkiewicz 1988. Prigogine & Nicolis 1967. Prusinkiewicz 2004. Veen & Lindenmayer 1977. Wolfram 2002). Evolving programming around embryology and botanic growth — where simulated digital biology may have been born (Brenner 2012. Reinitz 2012. Richards 2012. Swinton 2004) — was a pathway Turing used for computer simulations mimicking cognition and thinking performance. In a letter to neurophysiologist J. Z. Young, he wrote:

The brain structure has to be one which can be achieved by the genetical embryological mechanism, and I hope that this theory that I am working on may make clearer what restrictions this really implies. What you tell me about growth of the neurons under stimulation is very interesting in this connection. It suggests means by which the neurons might be made to grow so as to form a particular circuit, rather than reach a particular place (Turing 1951a).

Earlier in the letter to Young, Turing outlined overall research involving reaction-diffusion goals referencing brain functions, cellular switching, and metabolic growth:

- i) Gastrulation.
- ii) Polyagonally symmetrical structures, e.g., starfish, flowers.
- iii) Leaf arrangement, in particular the way the Fibonacci series (0, 1, 1, 2, 3, 5, 8, 13, ...) come to be involved.
- iv) Color patterns on animals, e.g., stripes, spots, and dappling.
- v) Patterns on nearly spherical structures such as some Radiolaria ... (Turing 1951a).

All five of his points relate to biology for computational investigation. Four days after writing to the neurophysiologist, Turing wrote to Michael Woodger (an assistant since 1946) that the Ferranti Mark I would begin arriving and: "I am hoping as one of the first jobs to do something about 'chemical embryology'" (Turing 1951b). The letters indicate research directed toward machine intelligence and they document evidence of intention on Turing's part to investigate nature by addressing questions of biological origin related to machines and code via mathematics (Allaerts 2003. Emmeche 1994. Swinton 2004. 2013).

Turing's drawings and computer simulated graphics thereby document field research used to investigate natural functions visualized on the way to programming code and Teletype printouts (Figs 26, p190. 28, p192). Those experiments interact theoretically with later programming and from them I mark an entry point for computational architectural simulation (Lindenmayer 1968. 1971. Lintermann & Deussen 1998. Meinhardt 1982. Prusinkiewicz 1994. 2004). As an example of how Turing's vision has been assimilated into design production and generative L-system-based software, I include experimental structures I digitally "grew" as simulated trees, branches, leaves, and seedpods to illustrate metabolic typologies with biorobotic action potential (Figs 6-10a, pp76-89). The line of theoretical evolution for these models, and the line of computational descent expressed in these pages, is best chronologically summarized from, but not quoted from Deussen & Lintermann's *Digital Design of Nature* (2010):

- 1) Turing 1936-1954 — universal machine, Turing Test, and morphogenesis research.
- 2) Aristid Lindenmayer, 1968 — L-systems code for biological simulation.
- 3) Deussen and Lintermann 2010 — Xfrog, plant generation.

Turing maintains pride of place in the above lineage of generative architecture; his reaction-diffusion and phyllotaxis drawings contribute to ongoing design evolution involving cognition, nature, and technology. Remember, computers including desktops, tablets, and smartphones, are according to Christopher Langton: "Turing machines — the formal equivalent of a general purpose computer" (Langton 1988 24). From computers and smartphones today, data critical to generative design, often accessed through extended phenotypes, is accrued by machine intelligence and may be streamed to the designer/student for verifying research, decoding, and sense-making (Dawkins 1982. Di Paolo 2005. Langton 1988). So, while Turing's drawings *visualize* nature pre- and post-computationally, they also illustrate pioneering attempts to use programming and machine intelligence to *decode* nature (Swinton 2004. 2013). Thereby, they help make sense of machinic questions Turing formulated such as:

May not machines carry out something which ought to be described as thinking but which is very different from what a man does? (Turing 1950 215).

And, seemingly on its way to hypothesize extended cognition, thoughts such as:

The extent to which we regard something as behaving in an intelligent manner is determined as much by our own state of mind and training as by the properties of the object under consideration (Turing 1948).

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5.3 • Morphogenetic Computation

Searching precedents for generative architecture, I found an unexpected acknowledgement of the universal Turing machine as an *idea* from Leslie Valiant:

... while for most ideas some long and complex history can be traced, the modern notion of computation emerged remarkably suddenly, and in a most complete form, in a single paper published by Alan Turing in 1936 (Valiant 2013 loc169).

Valiant's assessment, in conjunction with Wells's rereading of the universal *environmental* machine from Turing's, "On Computable Numbers, With an Application to The Entscheidungsproblem" (Turing 1936) points out still-evolving interpretations. In his differently focused reflection, Wells emphasized environment and objects as components in Turing's theoretical computation machine (Wells 2004. 2006). In doing so, he found environments and objects to be co-processors of data giving a different interpretation to universal machines; one

that dovetails with Clark's work on extended cognition (2008a). In this sense, Wells's reading connects environment and things to phenomenological affordances (Gibson 1986 127), that is, objects and environments temporarily bonding with their users and ambient, co-processing phenomenon. Wells's affordances then situate Turing's machine, environment, biological computation, and extended cognition in the realms of embodied, environmental biology and physical matter (Clark 2008a. Jonas 1966. Thompson 2007. Thompson & Varela 2001).

Wells inducts nature and objects into the workings of Turing's (1936) theory. Exploring Wells's logic obliges us to consider the universal Turing machine as a universal *environmental* machine — a shift countering dualism (Gibson 1986) and thus correcting what Thompson (2007 222) describes as, "the dualistic separation of consciousness and life [that] makes it impossible to understand coconsciousness in its basic form of bodily sentience." Associatively, Varela *et al.* (1992 202) countered dualism with: "We are claiming that organism and environment are mutually enfolded in multiple ways, and so what constitutes the world of a given organism is enacted by that organism's history."

In the configuration of a universal *environmental* machine, Wells's project stands against dualist obstruction I'm attempting to overcome for sourcing technological-aided biodigital and biomimetic data as it participates in cognitive extension (Clark 2008a). His hypothesis opens a way to conceptualize computation, machines, and environment consistent with autopoietic-extended design that thereby helps students conceptualize metabolic performance for architecture (Clark 2008a. Thompson 2007. Turing 1936. Wells 2004. 2006). Wells claims:

The Turing machine is an ecological model because it has parts representing the mind of the human computer and parts representing the paper and pencil environment. The success of Turing's work suggests that the ecological style of analysis should be developed for psychological domains other than numerical computation (Wells 2004 271).

Those "psychological domains" are, of course, cognitive domains where Wells situates universal environmental machinics between thinking and objects to conceptually bond them in an "ecological style of analysis" with cognitive-state objects such as "paper and pencils" (Wells 2004). (See p266, where Clark discusses pencil and paper as "responsible for the shape and the flow of thoughts and ideas"). Following implications from Wells, Turing's theory conceptualized cognition, computation, objects, and environment in computing machines before computers were realized. Therein, Wells's research in my reading finds Turing considering (or paving the way for) technology as continuous with environment and cognition. I see this proposition as an

autopoieticlike conclusion, recognizing that nature, non-linear and chaotic, cannot be excluded from allopoietic machines any more than it can be excluded from thinking or designing. In a synthesized cognition-in-the-environment frame, Lewontin elaborates:

The organism and the environment are not actually separately determined. The environment is not a structure imposed on living beings from the outside but is in fact a creation of those beings. The environment is not an autonomous process but a reflection of the biology of the species. Just as there is no organism without an environment, so there is not environment without an organism (Lewontin 1983).

If the ideas Wells brings forth are considered, we can see Turing's (1936) machinic theory as environmentally continuous, ongoing, and developed by factoring in wild and constructed nature through mathematics and objects/agents (including plants) as they help him to understand computation and cognition (Turing 1950. 1952. 1953). In like ways, Turing's drawings factor in botanic attributes as conduits to algorithms and simulations. Therein, Wells's (2004) hypothesis and Lewontin's (1983) scenario allow placing Turing's (1936) theory in line with his Turing Test (1950) and his later morphogenetic research (1952. 1953) as prefiguring biological simulation.

Scholars may debate Wells's interpretation, but calculating phyllotaxis or computing graphic output would not, from my point of view, be fanciful or out of bounds through Wells's universal environmental machine (Wells 1998. 2002. 2004). Therein, the 1936 universal machine heads a trail leading to Turing's (1952) experimental embryology in reaction-diffusion patterns, predictive algorithms, screen graphics, and teleprinter readouts (Brenner 2012. Dyson 2012a. Reinitz 2012. Richards 2013).

Compatible with Wells's (2002) hypothesis and Gibson's (1986) affordances, Andy Clark's (2001. 2008a) theory of extended mind and his subsequent research into prediction (2013a) detail how environments and objects are part of thinking. I propose Clark's theory (Chapter 7) engages object/environment ontology compatible with the working of Wells's (2004) universal *environmental* machine to see Turing's (1936. 1950. 1952. 1953) theories as progressively integrative between 1936 and his death in 1954. For now, I stand alerted to Wells's concatenations, suspecting that Turing may have, from his universal machine's inception (or soon after at Bletchley Park), considered machine physicality and embedded environmental decoding for computer programming as consistent with natural systems (Turing 1936. 1948. 1950. 1951. Wells 2004. 2006). In this light, Turing's morphogenetic project (1952. 1953) is a

logical extension of his lifelong observation of nature (Hodges 1992. Swinton 2004) interpreted in drawings, programming, and algorithms.

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While Wells analyzed and decoded the language in Turing's "On Computable Numbers" (1936), Jonathan Swinton unraveled mysteries in Turing's "The Chemical Basis of Morphogenesis" (1952). Swinton published a selection of Turing's morphogenetic plant simulations and drawings for the first time. He liberated Turing's Fibonacci phyllotaxis and reaction-diffusion pattern calculations from archival isolation, stimulating interest in the tasks these studies played in research related to mind, biology, computation, and nature (Swinton 2004. 2013). As the Turing Digital Archive (2014) shows, by the late 1940s and early 1950s, the morphological observations Turing undertook with fir cones and sunflowers found more than incidental expression in his drawings, notes, computer screen images, and programming (Fig 24, p188).

Less analytical and documentary, but earlier than Swinton, Allaerts tells us: "Turing's mathematical model of morphogenesis through chemical diffusible substances shaped a new domain for mathematical modeling in biology, named reaction-diffusion theory" (Allaerts 2003). Earlier still, Przemyslaw Prusinkiewicz and Aristid Lindenmayer situate Turing vis-à-vis computation and biology in *The Algorithmic Beauty of Plants*:

To computer scientists, Alan Turing is best known as the inventor of the Turing machine, which plays an essential role in defining the notion of an algorithm. However, biologists associate Turing's name primarily with his 1952 paper, "The Chemical Basis of Morphogenesis," which pioneered the use of mathematical models in the study of pattern formation and advocated the application of computers to simulate biological phenomena (Prusinkiewicz & Lindenmayer 1990 n104).

Beyond phyllotaxis, Turing (1951b) found reaction-diffusion potential for simulating forms, such as those found in radiolarians or patterns on cellular spheres (Richards 2005. 2013). He planned computational experiments looking to biological switching for chemical calculations conveying growth of "pattern[s] on nearly spherical structures such as some Radiolaria" (Swinton 2004 480. Richards 2013. Turing Digital Archive 2014 K/1/78). Turing was thinking about living structural growth, operations, and intelligence in metabolic-to-computation ways I categorize as biomimetic and illustrative of methods appropriate to investigation of nature via autopoietic-extended design (Benyus 1997. Estévez *et al.* 2003. Weinstock 2006a 27). Certainly he was thinking about analog life computed in digital machines to say:

Our new machine is to start arriving on Monday. I am hoping as one of the first jobs to do something about "chemical embryology" (Turing 1951b).

In light of Wells's reformulation of the universal Turing machine (Turing 1936) as a universal *environmental* machine (Wells 2004), phyllotaxis and embryological experiments take on relationships with scientific, machine, and natural exploration of computational metabolism, cognition, and machine intelligence now useful to building performance (Turing 1948. 1950. 1952). Jonas posited before Maturana and Varela, a variety of intelligence where:

The original condition of [an] organism, even on the unicellular level, exhibits individuality as the venture of freedom by which a form maintains its identity through the change of its matter (Jonas 1966 106).

Jonas's insight suggests a comparable way to interpret how Turing saw computational intelligence vis-à-vis reaction-diffusion as part of nature. If so, thinking or sense-making (as required to maintain "identity"), exemplified in Jonas's quotation, conjoined with Weber and Varela's (2002) and Di Paolo's (2005. 2008) sense of autopoiesis, unlocks processes to consider lifelike organisms as models and/or components for metabolic building systems.

Biological simulation postulated by Turing was advanced after his death, for example by his former student Bernard Richards (Fig 28, 192). In "Radiolaria: The Results of Morphogenesis," Richards (2013/1954 765) describes his process to prove Turing's postulate: "by solving the differential diffusion equations and examining the resultant observable shapes." In a process that explains graphic output, one familiar to Turing as well, Richards noted:

The computer involved, the Ferranti Mark I, had no visual display output facilities [sic], but only a very primitive line-printer restricted to numerical and alphabetic characters. So it was decided to . . . print contour maps of the [radiolarian] surface. . . . The pages were covered in the teleprinter symbols, each one representing a distance from the center (a height) on a scale of from zero to 31. Thus the whole surface of the sphere was covered. The writer [Richards] was then able to draw [Fig 28, p192] on these sheets the contour lines, locate the spines and record their lengths (Richards 2013 770).

For programming, Turing's coded biology preceded Lindenmayer's (1968. 1971. 1975) generative, L-systems. But it is L-systems that carried Turing's research into general programming and software for algorithmic cellular branching and botanic simulation now

common in generative design production (Deussen & Lintermann 2010. Wolfram 2002 893). This expression of design inheritance was still present (though highly evolved) when, for example, Rieffel *et al.* (2013 154) used L-systems for growing soft robots using videogame-engine physics simulators. Rieffel *et al.* (2013) described their process of digital evolution stemming from computational genotypes to biocomputational phenotypes:

Rule sets describe a developmental *process*, and thus they are an *indirect encoding* of a . . . physical phenotype. These grammars can be evolved by treating the rule sets as genotypes and the . . . results after a fixed number of iterations as the phenotype. . . . Thus, they are an indirect encoding of a physical phenotype (Rieffel *et al.* 2013 155 original emphasis).

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5.4 • Digital Biomimetics, L-Systems & Extended Turing

Architectural assemblages — machinics — or their component unities, potentially metabolic and/or intelligent, could be understood and investigated with design research methods similar to those Rieffel *et al.* (2013) discuss via genotype and phenotype. Thereafter, it may be through Lindenmayer's (1968. 1971) L-systems and Dawkins's (1982) extended phenotypes (Chapter 7. 7.4) that Turing's research plugs into current programming, generative architecture, and autopoietic-extended cognition in, what William Gibson (2010) identified as the "Digital Now."

Yet, to reach that Digital Now, a detour is necessary in order to register Lindenmayer's contributions to generative design. Those contributions sit on the timeline between Turing (1952) and current AI and living technology (Bedau *et al.* 2010. 2013) theorized early on by Beer (2004), Boden (1999. 2000), Langton (1988. 1996), Ray (1994), and Uribe (1981). Collectively, they suggest a continuum via computation that unambiguously leads into the present (Chomsky 1959. Lindenmayer 1968. Prigogine & Nicolis 1967. Prusinkiewicz & Lindenmayer 1990. Prusinkiewicz 1994. 2004).

Theoretical biologist Lindenmayer (1925-1989) was born the year after Sullivan published *A System*, and eleven years before Turing's (1936) universal machine. In the 1960s he developed a computer language for generative "development of organisms" where:

. . . the correspondence between the cellular arrays [organism components] we wish to consider and the strings of symbols one uses in abstract language theory is very close. Just as the theoretical linguists are concerned with the production rules or transformation rules by which certain types or words or sentences can be generated, so we are concerned with finding developmental instructions with which known kinds of

organism can be generated. Thus we shall consider the generating constructs of linguists called grammars (1971 456) . . . [Yet, our] systems differ from generating grammars in two important respects, namely the production rules . . . are to be applied simultaneously to all elements of a string, and the set of all strings generated is to be considered the language generated by the system (Lindenmayer 1971 461).

From a concept evolved from generative grammars (Lindenmayer acknowledges Chomsky's hierarchy of grammars), L-systems uses what Wolfram called "substitution systems" (Wolfram 2002 893) based upon *rewriting* sequences or, according to Langton: "recursively generated objects." Langton elaborates:

In the late 1960s, Aristid Lindenmayer introduced his mathematical models of cellular [automata] interaction in [biological] development, now known simply as L-systems. These relatively simple models are capable of exhibiting remarkable complex developmental histories, supporting intercellular communication and differentiation. Many applications have been found, especially in modeling the development of the branching structure of plants (Langton 1988 19).

In Lindenmayer or L-systems:

. . . rewriting is a technique for defining complex objects by successively replacing parts of a simple initial object using a set of *rewriting rules* or *productions*. The classic example of a graphical object defined in terms of rewriting rules is the *snowflake curve*, proposed in 1905 by von Koch (Prusinkiewicz & Lindenmayer 1990 1 original emphasis).

We have discussed analog morphology-to-design and morphology-to-drawing rule-based systems in Sullivan's *A System* (1999). Additionally, I document computational morphology represented in Turing's reaction/diffusion simulations (Fig 26 left. p190) prefiguring L-systems. Turing's programming — confirmed by Prigogine and Nicolis (1967) — exhibit a line of transformations through the expression of biochemical functions in living organisms mathematically described in algorithms (Richards 2013) to simulate emergent pattern formation and symmetry-breaking instability (Deussen & Lintermann 2000. Mandelbrot 1983. Reinitz 2012. Teuscher 2004. Turing 1952. Wolfram 2002 Fig C 191).

Building from Turing, Lindenmayer's (1968. 1971) theory has proven flexible in its ability to realistically simulate life-like graphic descriptions of complex botanic forms for art,

animation, and environmental simulation. It became one of the algorithmic growth engines propelling organic forms modeled for generative digital systems discussed in *A New Kind of Science*:

Independent of work in symbolic dynamics, substitution systems [rewriting] viewed as generators of sequences were reinvented in 1968 by Aristid Lindenmayer under the name of L-systems for the purpose of constructing models of branching plants . . . Work on L-systems has proceeded along two quite different lines: modeling specific plant systems, and investigating general computational capabilities. In the mid-1980s, particularly through the work of Alvy Ray Smith [cofounder Pixar], L-systems became widely used for realistic renderings of plants in computer graphics (Wolfram 2002 893).

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Returning to the Koch snowflake for a moment. In addition to being an example of a 1905 rule-based generative system it is an example of self-similar iterations causing a perimeter to increase indefinitely and thus approaches the definition of a fractal (Wikipedia 2013g). Iterative self-similarity results in unexpected consequences (infinite in situ recursion) when a boundless perimeter encloses a finite area. It also may be applied to theoretical models for analyzing biological phenomenon:

[I]n many growth processes of living organisms, especially of plants, regularly repeated appearances of certain multicellular structures are readily noticeable . . . In the case of a compound leaf, for instance, some of the lobes (or leaflets), which are parts of a leaf at an advanced stage, have the same shape as the whole leaf has at an earlier stage (Herman, Lindenmayer, & Rozenberg 1975 quoted in: Prusinkiewicz & Lindenmayer 1990 v).

L-systems provide part of the template for coding and simulating nature as required for biogenerative architecture to heuristically credit Turing's (1950-1954) vision characterized by his universal machine, decoded drawings, and coded simulations. Programming digital growth and branching from L-systems keyed possible infinite (fractal-like) recursion for computational graphics, while also making possible programmable stopping points required by architectural visualizations embedding biological mathematics in architectural simulations (Figs 6-10a, pp76-89).

Langton distinguishes ontological performance between nature and simulations where computational agents are not remotely (for my example) like plants, having no physical being but are rather information structures. He notes, behavior:

... as a whole does not depend on the internal details of the entities of which it is constituted [what matters are] the details of the way in which these entities behave in each other's presence. . .

[Nor does he claim they] capture *all* the nuances upon which . . . behavior depends. . . The critical point is that we have captured — within an aggregate of artificial entities — a *bona-fide* lifelike behavior, and that the behavior emerges within the artificial system in the same way that it emerges in the natural system.

The same is true for L-systems. . . The constituent parts of the artificial systems are different kinds of things from their natural counterparts, but the emergent behavior that they support is the same kind of thing: genuine morphogenesis and differentiation for L-systems (Langton 1988 33 original emphasis).

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In the Turing Digital Archive (2014) we find repeated evidence that Turing's morphogenetic research was built upon observation and study of plants and that his plant research was visualized and/or interpreted as sketches, drawings, or teleprinter transfers (Turing 2012 AMT/K/3). His process of observation manifested in drawings or algorithms, saw graphic production as shared between contemplation, drawing, and mathematics and thus machine programmable. Deployed today as observational process or method, biology meets digital simulation in drawings, texts, and/or code, then helps students enact biomimetic search and translation (Weinstock 2006a 27) to support metabolic research directed to generative architecture (Appendix 1) (Clark 2008a. Di Paolo 2005. Thompson 2007. Maturana & Varela 1980. Weber & Varela 2002).

Beyond informing biomimetic processes (Chapter 7. 7.5), Turing's drawings and notes are not directly, but *are* similarly, identifiable with how Richard Feynman characterized his own notes as "thinking on paper." Clark (2008a xxv) cited Feynman's view as an example of extended cognition and I reflect Clark's reading for extended cognition back upon Turing's work. In this context, I have surveyed the Turing Digital Archive (2014) for marginal drawings and note fragments to understand how Turing's *thinking on paper* was envisioned (or enacted) for machine performance. Largely, I conclude that Turing worked algorithmically to interpret attributes of nature and thus translate natural phenomena into mathematical code for machine

processing in order to frame and contemplate his own question: "Can machines think?" (Turing 1950).

That Turing used drawings — almost surely not thinking of them as art, yet distinguishing them from marginal or notepad sketches — is supported by archival material. The Turing Digital Archive's (2014) folder AMT/C/25, for example, contains miscellaneous manuscripts giving witness to his range of drawings, squiggles, plots, sketches, graphs, and illustration styles. A second archival folder, AMT/C/27 is relevant since it collects pages from the Manchester years specific to his morphogenesis project. To document one of his Fibonacci studies I superimposed his sunflower drawing of phyllotaxy (Fig 24, p188 top), onto the photo (Fig 24, p188 bottom) he used to trace its spiraling parametric growth (Thompson 1992/1917). The Photoshop composite illustrates basic data translation from nature in an easy for students to decode process that results in numerical and graphic information important to design visualization and computation.

While a few working sketches in AMT/C/27 are significant in line, style, or geometry, indicating that they functioned as process notes and "thinking on paper" (Clark 2008a xxv), more accomplished drawings such as (Fig 25, p189) demonstrate time-consuming composition, coloring, and execution. I read such works as Turing's attempt to visualize ideas formally, perhaps intending them to supplement publications and lectures. I think the holdings of the Turing Digital Archive (2014) supports the view that Turing established a drawing hierarchy distinguishable in greater commitment manifested in production, applied skill, and materials.

To accompany Turing's drawings, I searched remarks and anecdotes from archival letters, notes, testimonials, and the Turing centennial exhibition at the Science Museum, London (Fig 28, p192) for additional context (Lavington 2012. Rooney 2012). Sometimes this process helped extend analogies to new generative usages. Archival anecdotes point out, for example, ways Turing's colleagues saw drawings and computer-screen images, while sometimes identifying the machines that were used for his programming. Thereafter, phyllotaxis or reaction-diffusion graphics and coding are significant for registering the importance of Turing's insight into nature and AI vis-à-vis computation. That significance runs in conjunctions with physical computing machines and their combined impact on biogenerative design. (Copeland 2012. Dyson 2012a. Reinitz 2012. Swinton 2004).

Turing's drawings, in the above context, suggest observational design rearing bio-computational graphics and biological simulations capable of powering generative design (Deussen & Lintermann 2010. Floreano & Mattiussi 2008. Mattheck 1998. Prusinkiewicz & Lindenmayer 1990. Turing 1948. 1950. 1951. 1952. 1953). Furthermore, remarks by Turing's colleagues and former students — Richards (2005. 2013) on radiolarian digital generation for

example — aggregate bits of missing data in the Turing puzzle. Illustrating this point, Ferranti engineer J. M. Bennett recalls:

... with a random starting disturbance the final configuration was displayed on the Mkl's [Ferranti Mark I] monitors. It was always of interest to those of us watching to see what Fibonacci configurations would result (Bennett quoted by Swinton 2004 492).

After quoting Bennett, Swinton is cautious, suggesting that the patterns he saw were not expressions of phyllotaxis but of reaction-diffusion patterns: "Turing was certainly producing spotty [computer reaction-diffusion] patterns by 1953. It seems plausible that what the engineer saw was more similar to those, than explicitly Fibonacci patterns" (Swinton 2004 491). A bit earlier, Swinton explains: "Assessments of his [Turing's] progress between 1951 and his death on June 7th 1954 become correspondingly more speculative. There is no concrete archival support for that claim in 1951 to explain fircone patterns" (Swinton 2004 491-92). Yet, there seems to be disagreement. Copeland (2004 510) identified a sheet of Manchester programming, in Turing's hand. And, a related sheet in the Turing Digital Archive, AMT/4/27 Image 042, was titled by Turing "OUTERFIR" and identified by Hodges (1992 494) as a computer routine associated with fircone investigations (Fig 26, p190 right).

Swinton's argument is not critical to my thesis because my analysis is focused differently. The significance of computer programming and visualization displaying experimental data — phyllotaxic or distributed patterns between 1951 and 1954 — testifies to morphological research visualized algorithmically for screen or Teletype output and is itself historically noteworthy (Swinton 2004. 2013). My framing situates Turing's biological explorations with drawing and machine computation in roles illustrating generative graphic output incorporated into his creative and scientific processes (Dollens 2014).

Turing's computational reaction-diffusion programming foreshadows and contributes to L-systems. And Lindenmayer acknowledges Turing in his 1968 paper for *The Journal of Theoretical Biology*. Lindenmayer recognized that:

Ever since Turing (1952) proposed his famous morphogenetic models for shoot apices based on peaks and troughs of concentrations of morphogenetic substances which react with each other and diffuse around a ring, many developmental biologists have expressed interest in these kinds of explanatory hypotheses ... but no further use has been made of them. One of the reasons for this may be the mathematical complexity of dealing with simultaneous first- and second-order differential equations, as in Turing's

approach. The advantage of the theory proposed in the present papers is that only finite mathematics is used, and consequently it lends itself more readily to combinatorial manipulations, such as programming for digital computers, and the theoretical framework can be kept at a rudimentary level. At the same time results are obtainable which could be just as meaningful for morphogenetic considerations as those based on differential equations (Lindenmayer 1968).

Swinton (2004) notes publication by researchers extending "numerical approaches based on dynamic models . . . [where] some even used [Turing's] reaction-diffusion . . . Veen and Lindenmayer [1977] were the first to do this." Further, from demonstrations involving reaction-diffusion processes (Brenner 2012. Kondo & Miura 2010. Prigogine & Nicolis 1967) a lineage merges Turing's (1952. 1953) research, writings, drawings, scientific simulations, and computer graphics. That trail extends the impact of universal Turing machines (Turing 1936) with coded input programmed for machine output in graphic (Teletype) simulations. And, those simulations are looked at here as the seeds (or in Sullivan's word, *impulses*) of biogenerative architecture (Brenner 2012. Dollens 2014. Reinitz 2012. Turing 1952).

This merged Turing-Lindenmayer trail supports the idea that Turing's drawings and botanic algorithms were evolutionary steps leading toward experimental code resulting in computational biology. After all, this was the period after Turing (1950a) had written the *Programmers' Handbook for the Manchester Electronic Computer* and had outlined differential equations Richards (2013) later recalculated to digitally simulate embryological development of radiolarians (Fig 28, p192) thus jumpstarting generative computation. I conclude Turing directed his plant observation and drawing skills to help him conceptualize and analyze machine and programming performance vis-à-vis nature with his sights set to place code in the service of AI and ALife (Bedau 2003. Teuscher 2004a. Wells 2006). And, I think Richards's graphic radiolarian plots (Fig 28, p192) attest to the importance he and Turing gave to digital simulations (Richards 2013). Copeland (2004 508) concurs: "Turing was the earliest pioneer of computer-based ALife: he was the first to use computer simulation [Fig 26, p190] to investigate a theory of the development of organization and pattern in living things." Bedau concluded:

Alan Turing's pioneering work on cellular inhomogeneity over fifty years ago showed that instability in a homogeneous chemical system could generate the formation of patterns by a process of reaction and diffusion (Bedau 2003 508).

For my research, whether Bennett saw screen graphics illustrating phyllotaxis or reaction-diffusion is secondary to his seeing computational biology outputted to a video screen at all; a point not challenged by Swinton (2004). What is significant is that between 1951 and mid-1954 Turing was digitally simulating nature via digital processing and generative code (Fig 26, p190) to produce drawings and printouts as scientific data (Cooper & van Leeuwen 2013). At these levels of observation and programming output I establish Turing considering nature, numbers, algorithms, and machine processing through what for the first time may be termed *digital biomimetics*. This is significant for generative architecture delineated through L-systems in the context of today's computational generation as originating points of AI, machine-thinking, and 3D graphic simulation (Richards 2013. Teuscher 2004a. Wells 2006).

Therefore, the potential embedded in Turing's research involving human, plant, computation, and machine is sometimes held in data manifested in cognition, plant metabolism, biological cells, or computer code. That relationship of research investigation and translation through nature underpins methods in autopoietic-extended design and may be organized for student research (Brenner 2006. Clark 2008a. Lindenmayer 1968. Maturana & Varela 1980. Turing 1952). In autopoietic-extended design feedback — cognition-to-nature-to-machine-to-cognition — has earlier been called *machinic* (Chapter 1. 1.3). To review, *machinic* contextualizes computation and morphogenetic research to unify (as in autopoietic unities) primary research synthesizing biological nature, living technology, and machine intelligence (Bedau *et al.* 2010. 2013. Turing 1936. 1950. Wells 2004).

Machinic is thus a procedural formulation embedding Turing's work synthesized as an input/output (Hayles 1999) feedback loop — cognition-to-nature-to-technology-to-cognition. It's an emergent construct that opens research protocols, procedures, and methods to current practice (Clark 2001. 2008a. Maturana & Varela 1980. Turing 1936. 1950. 1953. Wells 2004. 2006). Turing's drawings then anchor a biologically inspired, computer-augmented design research continuum (Dollens 2014) emerging to algorithmically explore nature (Brenner 2012. Reinitz 2012). His computational and graphic visualizations are thus ancestors, extended-phenotype siblings; important to ongoing multidisciplinary developments in technology and design (Dawkins 1982. Turner 2000).

From this perspective Turing's digital simulations relate to today's learning community concerned with generative design and environmental bioremediation. The route targeted is through Lindenmayer's 1968 code for digitally simulating plants with L-systems (Floreano & Mattiussi 2008. Langton 1998. Lindenmayer 1968. Prusinkiewicz 2004. Prusinkiewicz & Lindenmayer 1990. Deussen & Lintermann 2010. Wolfram 2002). The L-systems lineage

suggests that theoretical, biological, and environmental repercussions are still emerging, Prusinkiewicz noted in 2004 that:

Models of plant architecture are based on the ecological concept of a plant as a population of semi-autonomous modules, and describe a growing plant as an integration of the activities of these modules. The mathematical basis for architectural plant modeling is most explicitly articulated in the theory of L-systems. L-systems harness the complexity of a multicellular organism by dividing modules into types. All modules of the same type share the same description (i.e. behave according to the same algorithm) . . . A distinctive feature of L-systems is that they give rise to a class of programming languages for specifying the models. This makes it possible to construct generic simulation software that is capable of modeling a large variety of plants, plant parts, and processes in plants at the architectural level (Prusinkiewicz 2004 80).

The notion of distributed agents (modules in the above) constituting intelligence as we have heard from Christopher Langton (Chapter 1. 1.3), agrees with Prusinkiewicz:

A living organism is *not* a single, complicated biochemical machine. Rather it must be viewed as a large *population* of relatively simple machines. . . . To animate machines, therefore, is not to "bring" life to a machine; rather it is to organize a population of machines in such a way that their interactive dynamic is "alive" (Langton 1988 original emphasis).

Both Prusinkiewicz and Langton, through notions of discrete agents, constructed and aggregated intelligence, reinforce the foundation from which Wells asserts:

Almost no one knows that the Turing machine is more accurately interpreted as an ecological rather than a solipsistic model (Wells 2004 271).

In the preceding three quotations, the first two involve code conceptualization, organization, and functions, the later a machinic-environmental assertion. Together they suggest new territory for mapping Turing's morphogenetic research (carried forward a decade later through L-systems) to situate the universal Turing machine as an environmental, cognitive, and computational processor (Wells 2004). Thereafter if mapped, the universal machine underlies (Chapters 1. 1.3 & 5. 5.2) approaches to metabolic, generative architecture and living

technology (Bedau *et al.* 2010. 2013) explicable for design through cognition, theory, biology, computation, and extended phenotypes (Clark 2008a. Dawkins 1982). In this sense we arrive at a situation where architectural modeling is a simulation tool for understanding nature as continuous and performative (Hensel 2006). The three above quotations (Prusinkiewicz, Langton, Wells) prompt me to pedagogically align Turing's drawings and plant programming in the role Hensel sees computational models playing today:

Advanced models incorporate the combined impact of gravity, tropism, contact between various elements of a plant structure, and contact with obstacles. The methodological setup, the toolset, and the choice of determining variables are equally interesting for architectural design. . . . While this type of modeling might have obvious theoretical and practical applications for biologists, it holds similar potential for architects and urban designers (Hensel 2006 14, 16).

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Manchester's Ferranti Mark I machine was delivered in February 1951 and Turing was eager for it. In a letter to the Ferranti engineer, Michael Woodger, Turing is waiting to begin morphological calculations involving "chemical embryology" (Turing 1951 in Swinton 2013).

This letter summarizes one area of Turing's intent while also creating a chronological marker. His expectation of Fibonacci numbers from fircone morphology would entail a process of decoding something like: *cognition-to-nature-to-cognition-to-computation*. As noted, the archive has fircone programming in Turing's hand for Manchester's computer (Copeland 2004 510).

We might now contemplate Turing's (1952. 1953) work as codebreaking nature via exposure to his search for chemical embryology (reaction-diffusion) to determine mechanisms of life-forming pattern, symmetry breaking, form, scale, and morphology (Fig 26, p190). The process, according to Hodges was finding an:

. . . explanation of how, granted the production of molecules by the genes, a chemical soup could possibly give rise to a biological pattern. He was asking how the information in the genes could be translated into action. . . . [T]o discover circumstances in which a mixture of chemical solutions, differing and reacting with each other, could settle into a pattern, a pulsating pattern of chemical waves; waves of concentration into which the developing tissue would harden; waves which would encompass millions of cells, organizing them into symmetrical order far greater in scale . . . a chemical soup [that]

could contain the information required to define a large-scale pattern in space (Hodges 1992 431).

Morphogenetic research for phyllotaxy or reaction-diffusion entailed biological switching and searching processes (Prigogine & Nicolis 1967. Reinitz 2012) related to cellular and metabolic control and command systems; for example Turing (1953) considered radiolarian growth and development (Richards 2013. Saunders 1992 98). Concurrent with Turing's morphogenetic research, Norbert Wiener (1965/1948) defined cybernetics as: "the scientific study of control and communication in the animal and the machine." Having met Wiener in 1947 (Hodges 1992 403) Turing was aware of his research, even if, according to Hodges, he remained aloof — perhaps sensing that: "cybernetics offered no immediate solutions to the problems posed by human beings" (Hodges 1992 412). Nevertheless, Turing's interest in computational search and control is documented in a particular contemporary project researched by Eberbach, Goldin, and Wegner and demonstrated in game programming:

... [W]e explore Turing's contributions to *Artificial Intelligence* (AI), of which he is considered one of the founders. ... [H]e envisions "intelligent" behaviors of future generations of computers. ... [Where intelligence is] viewed mainly in terms of *search strategy*; an intelligent agent is one that can find the best action based on current knowledge.

Turing identified chess as a good starting point for exploring intelligent search strategies. ... [He] and David Champernowne wrote the *Turbochamp* chess program in 1948, applying a search strategy known as *Minimax* towards choosing the next move, probably the first time this strategy was ever realized in computer code (Eberbach *et al.* 2004 168 original emphasis).

Understanding fircones, leaf patterns, and sunflowers visually and algorithmically might have likewise been part of Turing's 1950s conceptual approach to unlock computational procedures for experimenting with search, pattern, embryology, cognition, and machine intelligence. Confirming his focus around biology and cognition in 1947 he stated, "I am more interested in the possibility of producing models of the action of the brain than in the practical applications to computing" (Hodges 1992 363). In addition to the specifics of Turing's goals, the quotation establishes, if reflected through the metabolic plant research he undertook (Turing 1952. 1953), that his pursuit for computation was substantially through observation and contemplation of nature embodied in living matter.

Turing's archived drawings, seemingly scraps of evidence — what he called “drafts, notes, and calculations” (AMT/C/27), are waiting for further decoding. Perhaps the most satisfying image to unpack for design is a reaction-diffusion drawing thought to be among “the earliest uses of computer graphics in biology” (Swinton 2004 490). In it we encounter a hand-printed matrix illustrating pattern dispersal (Fig 26, p190) copied from a machine-processed teleprinter readout. Like paint-by-numbers, the background matrix plots the foreground morphogenetic shapes for hand plotting and shading. Once connected (outlined) as forms, the spots foreground machine-generated shapes as they mimic plant or animal pattern, camouflage, or dappling (See Richards 2013 p213 for a brief description of printing graphics at the Manchester University Computing Machine Laboratory).

At this point, I think we can see that Turing attempted to tap the processing power of computers to employ numerically translated biological events and forms into programming and graphics. Since chemical reaction-diffusion takes place throughout physiological/brain functions still being researched (Lefèvre & Mangin 2010), Turing was in advance of general mechanisms in order to analogously export nature's processes to machine intelligence (AI). Parsing the drawings and correlating descriptive fragments for a design perspective, my case study references visualizations with implications they foreshadow, for example in L-systems, autopoiesis, symmetry breaking, and generative design. Doing so connects the research drawings with biotechnology exemplified by three interrelated processes:

- 1) It documents morphological recursion, emergence, and scaling across nature using technology and design compatible with Maturana and Varela's (1980) autopoiesis and allopoiesis. This establishes theoretical relationships dating from the 1950s linking cognition, biology, technology, and environments with algorithms evolving from Turing's (1952. 1953) morphogenetic observations, drawings, and programming.
- 2) It suggests a logical starting block from which to discuss design involving computational biology and living technology visualized by hand drawing and algorithmic simulation, as well as establishing technological and computational infrastructures capable of integrating metabolic life into machinic and sense-making architectural bioremediation.
- 3) It connects to, and augments, points Clark makes regarding extended cognition, the parity principle, and data-embodied objects and environments as biologically connected with cognitive systems.

Point three, if referenced to Clark's work, "Reasons, Robots, and the Extended Mind," is then part of the connective tissue hybridized in this text as autopoietic-extended design (Clark 2001b. 2005. Maturana & Varela 1980). As Clark reflects: "a special kind of hybridization in which human brains enter into an increasingly potent cascade of genuinely symbiotic relationships with knowledge-rich artifacts and technologies" (Clark 2001b 2). In his essay, Clark (2001b) talks about sketching as cognition-to-environment active:

The sketchpad [Here: Sketchbook app Fig 16, p158 middle] is not just a convenience for the artist, nor simply a kind of external memory or durable medium for the storage of particular ideas. Instead, the iterated process of externalizing and re-perceiving is integral to the process of artistic cognition itself (Clark 2001b 18).

Clark finds drawing as environmentally collaborative — cognitive agent responding to environmental input by sketching output — in this, environments are generative participants inseparable from cognition. Further, he situates cognitively extended actions or objects (extended phenotypes) such as drawings, alongside biorobotic and biomimetic research citing, for example, phonotaxis in crickets as related to objects, matter, and organisms in physical and thought environments (Clark 2001b. 2005. 2008a. Webb 1996. 2001).

For Clark, the locations of perception, transmission, and embedded intelligence are in brain/body/object situated in shared cognitively engaged environments. That formulation is compatible with Wells's universal *environmental* machines and this paper's consideration of smartphones as universal and environmental machines (Dennett 1998. Langton 1988) streaming data to cognition (Wells's 2004. 2006). If Turing considered interconnected machine actions and environments (the machine as a sub-environment) in ways Wells suggests, and I think he did, we may introduce Wells's reading to Clark's theorizing and postulate Clark/Turing correlations (Clark 2001b. Turing 1936. 1950. Wells 2004. 2006).

Those Clark/Turing/Wells bonds fortify methods for generative design conceptualizations via cognition/computation/environment that translate into procedural methods for autopoietic-extended design methods (Appendix 1). The common ground between Turing, Clark, and autopoiesis then lies not in machines or the Turing Test but in a conceptualized, cognized, and observed view of environment, objects, and nature — as Varela *et al.* (1992 200) surmise: "cognition is not representation but embodied action and that the world we cognize is not pregiven but enacted." "Embodied action" resulting in student ideas thus initiates procedural operations reproducible for design research and possible machine and code programming (Fig 26, p190).

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Today, Turing's morphogenetic research haunts computational simulation and algorithmic generation involving the transference of metabolic attributes to design simulation. In transference, his historic research must be adjusted and updated in light of consequent events and subsequent experimentation grounded, but not foreseen in his work. If we now see beyond his projections and drawings, it behooves us to remember Newton's description of seeing farther by standing on the shoulders of (scientific) giants. We look, we see, and we communicate in terms Turing never did; but we do so, to a great extent, from his shoulders, work, and vision.

Recalling Sullivan's proto-shape grammars (Chapter 4. Figs 15-19, pp157-161), biopatterns, branching, and physical growth considered in the domains of drawing, scaling, spiraling, and curving are native to generative design, parametric software, and algorithmic architecture (Prusinkiewicz 2004. Prusinkiewicz & Lindenmayer 1990. Richards 2013. Thompson 1992/1917). Their interactions communicate natural growth, computation, and form development foundational to digital generative design. Subsequent research and software programming after 1960, exemplified here by Lindenmayer (1968) and Prigogine and Nicolis (1968), verified and extended Turing's research to produced branching lattices, spiraling growths, recursions, animation, and pattern formations. For design, advances in programming, software, and technology brought mathematically responsive potential able to simulate natural attributes for buildings (Deussen & Lintermann 2010. Floreano & Mattiussi 2008. Lynn 1999. Prusinkiewicz & Lindenmayer 1990).

Turing's use of plant forms marks a vision for research documented in his surviving drawings (Figs 24-27, p188-191). His morphogenesis experiments display botanic performance in models situated between cognition, technology, and environment (Turing 1952. 1953). Turing demonstrated, in the course of a few personally distressful years, a method of low-tech morphological observation and powerful technological analysis exhibited in theory, drawing, and machine programming (Turing 1948. 1950. 1951. 1952. 1953). His lifelong observation and decoding of plants and their ramifications between technology and nature is verified and only entering our understanding of his working processes (Allaerts 2003. Brenner 2012. Cooper & van Leeuwen 2013. Copeland 2013. Dollens 2014. Hodges 1992. Richards 2013. Swinton 2004. 2013).

According to his biographer Andrew Hodges (1992 208), at one point while at Bletchley Park, Turing carried a fircone around in his pocket for Fibonacci study and discussion. Years before, his mother, Sara Turing (2012) sketched him occupied with a daisy, oblivious to his football teammates continuing the game. Apparently and evidently, he was genuinely receptive to first-hand observations of growing, morphing things. From these and other stories, I conclude

that Turing's research may be seen as a methodological seed (in Sullivan's sense, Chapter 4) worth reengineering in digitally savvy pedagogies for research and visualization methods involving intelligence, plants, and nature.

Alan Turing did not leave procedural guides; basic tactics must be imputed for an OS analogy where nature, phenomenological cognition, and computation play side-by-side roles. Toward this goal, I outline three takeaway lessons:

- 1) That Turing practiced drawing and in-field observation of nature as part of his computational research in order to understand, process, and translate biological attributes to coding.
- 2) That his drawings participated in his thinking as cognitive extensions supporting recursion between observation, visualization, mathematics, and computational processes used to experiment with AI, programming, and graphic simulations consistent with autopoietic-extended design.
- 3) That morphological and metabolic processes could be 3D computer simulated and 3D printed for dynamic analysis, leading to scripted architectural generation and metabolic bioremedial performance.

Today, biocomputational architecture conceptually filtered as machinic, biodigital, or generative may be integrated into the digital heritage initiated by Turing machines, codes, drawings, simulations, and visualizations (Dollens 2014. Estévez *et al.* 2003. Lindenmayer 1968. Lindenmayer & Prusinkiewicz 1988. Prusinkiewicz & Lindenmayer 1990. Deussen & Lintermann 2010. Wells 2004). Thereafter, because of flexible programming, biological simulation, and machine processes in generative design, Turing's role may be plotted as ongoing heritage rather than as a series of discrete, unconnected contributions. At this stage, when I ask: Can buildings think? generative architecture reverberates differently from the question's seemingly rhetorical role in Chapter 1. The long-running question is now positioned amid metabolic and phenomenological domains of Turing's morphogenetic project (1952. 1953), his technological innovations, and his digitally programmed simulations recursively referencing: "Can machines think?" (Turing 1950).

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Chapter 6 • *The Cognitive Life of Things* • Smartphones, Complexity & Learning

Searching for Andy Clark's "Material Surrogacy and the Supernatural" (2010a) I discovered Lambros Malafouris and Colin Renfrew's *The Cognitive Life of Things* (2010). Signaled by its title declaring that objects had cognitive/metabolic attributes — life — I thought to explore the book's archaeological research for overlap with design research. But, I found additional prospects. *The Cognitive Life of Things* investigates phenomenological-to-cognitive environmental relationships in the context of extended cognition, material intelligence, archaeological theory, landscapes, and cultures. The book embraces processes to investigate mind's relationship to things-in-the-world as cognitively extended.

Moreover, *The Cognitive Life of Things* reverberates with discussion of intelligence in the environment — houses as intelligent objects for example (p236) — from which I reflect on how Turing (1948. 1950. 1951. 1952) may have sensed environmental and biological intelligence and looked to nature for insight into coding and AI (Clark 2001b. Copeland 2012. Hodges 1992. Wells 1998. 2002). I infer that archaeological working *things* include machines commonly referred to here as architecture, and I locate smartphones as intelligent devices partly evolved from Turing's ideas of intelligent machinery (Turing 1948. 1950. 1951).

Smartphones in this context reinvent prosthetic tools (Haraway 1990) relative to Clark's (2003) *Natural-Born Cyborgs* as AI data-sourcing machines assisting cognitive communication. Furthermore, as handheld, dispersed universal Turing machines (Copeland 2013. Dyson 2012a. Wells 2004) smartphones and apps are devices capable of providing increased research and communication options giving bearing to gamelike strategies and performance (Chapter 1. 1.7) (McGonigal 2011), design-learning tactics (Fenwick *et al.* 2011), and in-field design production (Google 2013. Malafouris & Renfrew 2010. Turing 1936. 1950. 1951).

Tasked for autopoietic-extended design, smartphone/apps are performance devices servicing emergent ideas and communication through data retrieval and dispersal (Floreano & Mattiussi 2009. Frazer 1995. Hensel 2012. Spiller 2009. Spiller & Armstrong 2012). I explore Malafouris and Renfrew's chapters for discussion of made, constructed things (including houses, landscapes, and smartphones), with data retrieved and interpreted through participatory cognition and technology. Hence, the play of cognitive *things* to architecture illustrates potential ontological lessons capable of contributing to pedagogical insight (Clark 2013. 2013a. Fenwick *et al.* 2011. Malafouris & Renfrew 2010). My insertion of smartphones as data conduits then programs inclusion of mobile computation, hand-held drawing devices, and group communication systems to enable in-field research (Allaerts 2003. Copeland & Proudfoot 2004. Swinton 2004 2013. Turing 1952. Turing 2012).

The Cognitive Life of Things itself exemplifies research investigating houses, objects, tools and their production in shifted historic time frames from those of architecture, but the book is compatible with design learning and production methodologies contemplated here (Malafouris & Renfrew 2010). According to the books' back cover: "Things have a social life. They also lead cognitive lives, working subtly in our minds" (Malafouris & Renfrew 2010). Clearly, these words hold deep resonance for architecture and technology. I therefore track some of the ideas for methods of applied extended-cognition to survey objects and architecture (Malafouris & Renfrew 2010) in conjunction with autopoiesis (Maturana & Varela 1980).

I suggest that through *The Cognitive Life of Things* architecture and archaeology's relationship to ancient craft facilitates parallel analogies with tools, learning, materials, and environments (Herrmann 1984. Jonas 1966. Malafouris & Renfrew 2010). From those analogies, I also conclude both archaeology and architecture involve autopoietic processes — cognition-to-environment decoding of reality (Lettvin *et al.* 1959. Maturana & Varela 1980). Here too, extended cognition sources architecture as objects, things, and/or machines in the environment.

Extended cognition, aided by autopoiesis may further help recognize and detail (Di Paolo 2005. 2008. 2010) metabolic intelligence for buildings following a logic referenced in genotype/phenotype/extended phenotypes as an expression of being in nature (Sections 5.2 & 7.5) (Dawkins 1982. Hansell 2005. Langton 1988. 1996. Odling-Smee 1996. Weber *et al.* 2013). In this light, *The Cognitive Life of Things* contributes to discussion of metabolism, objects, and forces in nature as components of architectural systems (Jonas 1966. Malafouris & Renfrew 2010. Turing 1950). The book demonstrates processes synthesizing objects-in-environments with thinking-in-environments to strengthen fundamental arguments similarly flowing around autopoietic-extended cognition.

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6.1 • The House as an Intelligent Object

Chris Gosden's essay in *The Cognitive Life of Things* is titled: "The Death of the Mind." Its first sentence reads:

In this chapter I shall argue that the concept of mind has outlived its usefulness and should be replaced with more varied alternatives (Gosden 2010 39).

The gist of this assertion I apply to architecture where dated concepts of the individual architectural genius and a priori visualization, "has outlived [their] usefulness" leaving environmental, educational, and professional liability. Toward this end, I read in Gosden's essay constructive ways for locating mind and design in nature (Jonas 1965). Gosden first asks:

Does the inside space [referencing mind/body] exist within the head, is the skin the boundary between the self and the rest of the world or does the intelligent self project itself outside into the world in some way? (Gosden 2010 39).

This question echoes Clark and Chalmers's (1998) "active externalism" and "parity principle" evolved in Clark's later writings (Clark 2001a. 2003. 2005. 2008a. b. d. Menary 2010). Below, Gosden continues and targets the phenomena of mind as spatially aligned:

Current attempts to rethink mind have extended the spatial metaphor, so that intelligence arises in and through things as well as people. . . . These ideas see mind as not located in our heads, but something which comes about through the interactions of the whole human organism with its world, so that intelligence resides in action as much as thought and in the social use people make of the object world (Gosden 2010 39).

Gosden's "intelligence arises in and through things. . . . through the interactions of the whole human organism with its world" (2010 39), depends upon receptor-senses participating in distributed urban and wild nature. Spatial occupation therefore makes learning situations possible — not only through knowledge construction or knowledge replication (Fenwick *et al.* 2011 33. Luhmann 1990a. 2000) — but through events, objects, and phenomenon: "intelligent things and the intelligent landscape" (Gosden 2010 40). Varela calls this type of knowing the organism's "descriptive repertoire:"

. . . always a reflection of ontogeny of the knower, because ontogeny as a process of continuous structural change without loss of autopoiesis is a process of continuous specification of the behavioral capacity of the organism, and hence of its actual domain of interactions. Intrinsically, then no "absolute" knowledge is possible, and the validation of all possible relative knowledge is attained through successful autopoiesis or *viability* (Varela 1979 48 original emphasis).

In a framework of spatial occupancy, constructing knowledge entails a process of individual perception, interpretation, and creativity (Lettvin *et al.* 1959. Luhmann 2000). With Gosden's (2010 39) "intelligence arises in and through things" vis-à-vis Varela's above "continuous specification," I buttress notions that biodigital design education may occupy specific physical research locations as sources of autopoietic learning communication and

input/output. And, that physical occupancy of a research site, includes mobile technology as spatially and cognitively enhancing. To reinforce the call for occupancy of learning and research environments, I turn to Hans Jonas:

... without the body by which we are ourselves an actual part of the world and experience the nature of force and action in self-performance, our knowledge — [is] a merely "perceptive," beholding knowledge (Jonas 1966 20).

In autopoietic-extended design, interactions between archaeology and architecture are phenomenologically, theoretically, and materially affinitive (Clark 2008a. Gibson 1986). When Gosden posits, "intelligent things and the intelligent landscape" (2010 40), he does so with strong ideas defining "landscape" — built and natural — as *bringing forth* cognition. In this sense, *bring forth* is nature collaborating through cognition to co-generate thought and ideas and thereafter architecture (Clark 2008a. Malafouris & Renfrew 2010. Maturana & Varela 1980). Bringing-forth for design and learning then potentially realigns object properties, attributes, and phenomenological data as technologically communicable and subsequently available to student decoding for constructing design information (Luhmann 2000). Here with an architectural example, Gosden concurs:

A home is both a physical setting — a house — and a domestic group related through blood and marriage. It speaks of shared activities with a defined physical space, tensions, intimacies, and boredom in changing mixtures. . . . *The house is an intelligent object*, condensing many of the key relations of an intelligent landscape, and having an undoubted effect on human bodies and brains. Houses are not mental extensions, but containers, shapers, and complex products of human action all at once (Gosden 2010 41 emphasis added).

While I disagree that, "houses are not mental extensions," Gosden places an unmistakable call for intelligent landscape interpretation punctuated by objects as integral to cognition (2010 41). I then subscribe to: "The house is an intelligent object" (Gosden 2010 41). In that subscription I hear echoes of Modernism (Chapter 2) paralleling Sullivan's (1979 170) "form ever follows function" (Chapter 4) and Le Corbusier's (2007) "a house is a machine for living in" as they continue onward to Turing's (1950) "Can machines think?" (Chapter 5).

Gosden advocates reading archaeological artifacts as participants in intelligence; in this sense I find generative environmental communication. But extrapolating from a modern object

is also communicative, sensual, and capable of phenomenological engagement. "The house is an intelligent object" (Gosden 2010 41) is then a startling thought for architectural evaluation: perhaps controversial. It suggests shifting our attention and interpretations of architecture and urban constructions to be contingent and co-generative with nature — because, intelligence is a natural phenomenon. Further, this suggestion is in tune with architecture as extended phenotypes (Dawkins 1982. Hansell 2005). Hereafter, shifting our attention implicates environmental-data input and coevolved design functions as environmentally arising for the creation of intelligent (metabolic) buildings. Gosden's ideas thereby suggest an autopoietic-extended design trajectory for a different account of how design input could be pedagogically oriented through smoother cognitive integration with nature (Gosden 2010).

To continue, I reference Gosden's writings to a companion essay in *The Cognitive Life of Things* by Niels Johannsen (2010 59). Johannsen discusses creativity compatible with Gosden's views on intelligent landscapes:

Technological change also depends on concrete processes of creative thought, which are based on the cognitive ability to reconfigure certain aspects of the world. To proceed, we must also come to grips with the occurrence — on a scale unlike any other in the biological world — of such cognitive leaps (Johannsen 2010 61).

I take Johansen's "cognitive ability to reconfigure certain aspects of the world" (2010 61) to encompass extended phenotypes (Dawkins 1982. Hansell 2005. Turner 2000), and as appropriate to autopoietic-extended design (Sections 5.2 & 7.5). After Gosden's (2010 39) consideration of landscapes and "object world," and Johannsen's suggestion of cognitive leaps of creativity, I divert their ideas to confront architectural pedagogy and practice (Barnett 2007. Bayne 2008. Davis 2008). The resulting assemblage considers dispersed intelligent and cognitive environments as interlinked through a student's physical and pedagogical habitat in ways technology can magnify. Because both Johannsen and Gosden addressed archaeology does not preclude the fact that what they are talking about is learning in, from, through, and with landscapes. Here, Johannsen paraphrases Kim Sterelny:

... human alteration of environmental niches implies an element of "downstream epistemic engineering." Sterelny emphasizes that human action structures the learning environment of other individuals in the group and that of subsequent generations, and that this enhances the acquisition of skills, which are appropriate in context (Johannsen 2010 61).

Again, the realm of extended phenotypes (Dawkins 1982. Hansell 2005. Rieffel *et al.* 2013. Turner 2000) does not seem remote from Johannsen's: "human action structures the learning environment" (2010 61). The quotation from Johannsen is a consideration of learning-receptivity involving skill transmittal not only in intelligently interfacing environments, but also in consciously distributed, shared, and cultivated environments (Clark 2008a. Noë 2009. Thompson 2007. Turner 2000). Furthermore, the quotation permits extension toward digital games as virtual learning cartographies that enhance connections with digital spatial realms, electronic devices, extended phenotypes, and environmental strategies (Dawkins 1982. Gee 2007. McGonigal 2011. Wark 2007). I think this is then one (of many potential) autopoietic-extended design components able to support cognitive extension theory where extension is augmented by ubiquitous technology. And, where the implementation of e- or m-learning is referenced to student technological experiences and virtual worlds associated with social media and videogames. Jane McGonigal, in no uncertain terms concurs:

Gamers, without doubt, are reinventing what we think of as our daily community infrastructure. They're experimenting with new ways to create social capital, and they're developing habits that provide more social bonding and connectivity (McGonigal 2011 93).

McGonigal's structuring "social bonding and connectivity" is not oriented in single directions or in single intuited acts; it's phenomenologically more akin to natural forces dispersed in nature (Clark 2003. 2008a. Jonas 1966. Odling-Smee *et al.* 2013). Johannsen reinforces modes of structuring body memory as machinic, suggestive of gameplay that transfers to other areas of technological embeddedness, usages, or physical training for perceptual understanding of spaces and landscapes (Gee 2007. Wark 2007). Johannsen states:

... physical experience is stored in bodily memory, probably as cross-model collections of modality-specific impressions particular to given phenomena ... and is then employed (simulated) when facing a conceptual challenge at a later point in time (Johannsen 2010 63).

Asking students to extrapolate ideas from an environment, landscape, tree, or building embodies physical, mental, spatial, and sensory memory and imagination in ways Johannsen discusses. I think if an autopoietic-extended design OS is conveyed as an infrastructure, students

have the potential to configure it to their research needs — to reference and tune (Coyne 2010) it in ways akin to Johannsen's (2010 63) "modality-specific impressions." And, to equally draw upon current digital culture for methodological and technological experience where many students have know-how from videogames and social media portable to m-learning (Pew Internet 2006. Oxford Internet 2013). Johannsen further directs us to experiences that may be translated as design opportunities:

Technological experience may, in other words, play a decisive role in creative cognition. The same is true for the human body and for all kinds of other life forms, structures, and events of the natural world. However, through their involvement in technological practices, humans repeatedly provide themselves with experiences of functional or causal relationships and dynamics that they would not necessarily have had the opportunity to experience in some imagined, non-technical human life. These experiences are then used opportunistically in conceptual processes (Johannsen 2010 63).

Self-mediated causal relationships are also "opportunistically" supported in *The Phenomenon of Life*:

The experience of living force, one's own namely, in the acting of the body, is the experiential basis for the abstractions of the general concepts of action and causation (Jonas 1966 22).

Between Johannsen's (2010 63) view of technologically mediated experience and Jonas's (1966 22) bodily enactions, I think there is a possibility of new design learning spaces involving both highly sourced technological data simultaneously with physical observation and tactile perception. I relate Johannsen's "conceptual processes" to emergent cultivation or even "causal" procedures for configuring autopoietic-extended design and thus as a programming aid for pedagogical methods. Here then, I propose cognition partners technology via smartphones for design learning.

Johannsen plots cooperation as technically enhanced, dispersed creativity feeding cognition:

The combination of cooperation and potent technology is probably one of the few most important factors behind the success of the human species. . . . [D]iscussion . . . has

attempted to identify mechanisms that could be responsible for the continued human technological creativity on the same genetic hardware, and has stressed the importance of associative conceptualization (Johannsen 2010 64).

To then interface Johannsen's archaeological position with complexity in educational theory, an engrained, deeply rooted, ontological problem becomes apparent. Fenwick *et al.* critique it below as a traditional educational point-of-view, countered by complexity theory:

The problem is that education has come to treat knowledge as centrally a matter of representations, texts, and theoretical models that offer presentation purporting to copy a reality that pre-exists them. Learning is then understood to be a matter of acquiring the knowledge contained in these re-presentations. But complexity refuses to separate knowledge from reality as through they exist in different spheres of participation where mind is divided from the world. Instead, the world and our knowledge of it emerge together. An emergent epistemology counters the representationalist epistemology of schooling (Fenwick *et al.* 2011 33).

Reinforcing Fenwick *et al.*, Brent Davis brings insight to complexity and systems theory:

Knowledge-producing systems . . . are among the phenomena that are studied by those interested in systems theory, one of the major tributaries to complexity thinking. Systems theorists focus in large part on living systems, seeking to understand the manners in which physical systems self-organize and evolve. These systems include brains, individuals, social collectives, and cultures (Davis 2008 52).

And Davis makes an observation that carries throughout autopoietic-extended design discussion:

A system of ideas is indeed transcendent of a material system; hence, knowers and knowledge can be considered separately, even if they cannot be considered separate. One cannot exist without the other; they are enfolded in and unfold from one another (Davis 2008 53).

Finally, Davis sees the necessity to activate complexity theory in the practice of education theory:

... emphasis in complexity research has shifted beyond careful accounts of complexity phenomena toward deliberate attempts to prompt the emergence and affect the character of such phenomena (Davis 2008 58).

Complexity from Fenwick *et al.* (2011) and Davis (2008) root the bigness of autopoiesis and extended cognition. And Johannsen's "associative conceptualization" (2010 64) seems a just-in-time concept minted for architecture learning not predicated on a priori idea generation or "reality that pre-exists" (Fenwick *et al.* 2011). For autopoietic-extended design I look to evolve parameters for seeking living design data by focusing within encompassing nature to an emergent, albeit specialized, design epistemology organized in distributed and ubiquitous smallness, via first-hand — bottom-up — student sourcing of pedagogical data (Davis 2008. Fenwick *et al.* 2011. Johannsen 2010. Maturana & Varela 1980). As Langton described earlier: "A living [learning] organism is *not* a single, complicated biochemical machine. Rather it must be viewed as a large *population* of relatively simple machines" (Langton 1988 original emphasis).

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6.2 • Emerging Approaches to Educational Research

Case study comparisons between architecture and archaeology filtered by complexity theory may seem problematic for design research and education — non-aligned — essentially occupying different time frames, protocols, and intentions. Yet as I have indicated, if archaeology is an analysis of artifacts and past-in-present-environments, like design education, it values methods of literacy, materiality, territorial mapping, and semiotic decoding for data and artifact interpretation (Malafouris & Renfrew 2010). Related, complexity theory discussed here by educators, frames non-linear data, phenomena, and cognition for emergent pattern interpretations (Davis 2008. Fenwick *et al.* 2011. Mason 2008a. b).

My specialized overview of archaeological research looks to parallel developments for recognizing and comprehending things and places via *decoding*, *marking*, and *making* in historical design continuums (Malafouris & Renfrew 2010). I'm reviewing archaeology that, like autopoietic-extended design, looks to extended cognition to understand how cognition-to-environment theory could be articulated in conjunction with architectural history, new technology, and current practice (Clark 2008a. Gibson 1986. Jonas 1966).

In conjunction, recent educational theory considering risk, environment, and experimentation (Barnett 2007. Bayne 2010) develops a point-of-view by placing an emphasis on socialmaterials (objects engaging cultural dialectics in an environment) to demonstrate receptivity to methods for learning. Educational theory does so considering the socialmaterial

(Fenwick *et al.* 2011) in dynamic emergent environments. The production of knowledge realized in an engaged environment then allows pedagogical comparisons to open research exploration between disciplines or varying objects. Fenwick *et al.* tells us:

Socialmaterial approaches highlight the actual processes of boundary-making that create education phenomena and produce knowledge and objects. They trace the actual dynamics through which powerful entities and linkages are assembled, reassembled and occasionally transformed, showing how they can be disassembled but also moved forward in the course of assemblage (Fenwick *et al.* 2011 viii).

Generating, interpreting, or assembling points-of-view — learning and knowledge construction — then influences perception of pliable, chaotic data in the creation of design (Barnett 2007. Lettvin *et al.* 1959). Those experimental results confirm input/output (feedback) data affecting the construction of reality; subsequent design realization then applies not only in education or knowledge construction (Luhmann 1990 69) but also evolves design learning (Barnett 2007. Bayne 2008. 2010. Burns 2000. Davis 2008. Fenwick *et al.* 2011. Gee 2007. Mason 2008a. b). As we shall see with extended cognition in the next chapter, spatial environments and objects beyond classrooms come under consideration as educational hosts, for example:

Spatiality orientations are concerned with how space is shaped, altered, colored, refracted by the human activity within it, and how space arrangements alter human movement, identifications, and meanings (Fenwick *et al.* 2011 3-4).

That quotation is from educators, not designers. Reading nontraditional learning spaces as meta-environments in *Emerging Approaches to Educational Research* strengthens the OS scaffolding contemplated here as infrastructure (Clark 2008a. Gibson 1986. Fenwick *et al.* 2011). Spatial metaphors then fit design learning with *Emerging Approaches*: “how systems and practices and knowledge become more or less connected [structurally coupled in autopoiesis], performing comparable . . . activities across space-time” (Fenwick *et al.* 2011 5). The book’s authors, Tara Fenwick, Richard Edwards, and Peter Sawchuk suggest that we: “Consider the concept of learning, [as] central in educational discussions and extremely slippery in meaning” (Fenwick *et al.* 2011 5). They emphasize:

It is by now commonplace in educational theory to understand learning as more than the purely individual, cognitive, and acquisitive process that has driven some educational approaches. Conceptions of learning have long acknowledged the importance of transactions among concepts, language, cultural mediation, and experimentation with environmental objects. Notions of learning as socio-cultural participation, embedded in particular joint activity, tools, and routines, have become ubiquitous in education (Fenwick *et al.* 2011 5-6).

Key words, phrases, and concepts from the above bank in the direction I implement throughout autopoietic-extended design. “Experimentation with environmental objects,” “cultural mediation,” and “embedded” are processes and/or concepts that within my thesis have appeared from the beginning (Fenwick *et al.* 2011 5-6). Precedents (and later architectural models) show need of wider experimentation supported by theory intended to nurture cross-disciplinary hybridization; I attempt to address this need with learning exercises demonstrated in the Student Handbook (Figs 1, p29. 2, p44. 3, p45. 11, p93. 29, p278. 30, p279 & Appendix 1). Fenwick, Edwards, and Sawchuk situate such ideas of objects, materiality, and processes in education hauntingly close to extended cognition:

As the material is not secondary, but integral to the human, it is through the being-together of things that actions, including those identified as learning, become possible. Learning is an effect of the networks of the material, humans and non-humans, that identify certain practices as learning, which also entails a value judgment about learning something worthwhile. Thus teaching is not simply about the relationships between humans, but is about the networks of humans and things through which teaching and learning are translated and enacted. Teaching and learning do not exist, and cannot be identified, separately from the networks through which they are themselves enacted (Fenwick *et al.* 2011 6 original emphasis).

In complement, learning and design research methods proposed for autopoietic-extended design look to enacted networks compatible with those proposed by Fenwick *et al.* (2011). They do so with similar teaching and learning intentions for connectedness, process, morphology, and aesthetics to ultimately stakeout domains for constructing design knowledge (Clark 2008a, Fenwick *et al.* 2011. Maturana & Varela 1980). And for design, we must add materiality in categories of making and marking to (sometimes) converge in data and idea generation:

The *sine qua non* of cognition, then, is materiality. As Merleau-Ponty has argued, “perception and representation always occur in the context of, and are therefore structured by, the embodied agent in the course of its ongoing purposeful engagement with the world.” . . . Damasio has located the deep roots for the self “in the ensemble of brain devices which continuously and *nonconsciously* represent the state of the living body” . . . and argues that this proto-self — not restricted to humans — provides the raw material for narrative construction of the secondary “core” and “autobiographical” selves (Coward & Gamble 2010 48 original emphasis).

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Extended mind thesis is taking root in fields of social sciences, science, philosophy, art, education, and humanities (Bolens 2012. Clark 2008a. Fenwick *et al.* 2011. Luhmann 1990. 2000. Malafouris & Renfrew 2010. Thompson 2007). In looking to academic and theoretical archaeology, as well as generally referencing ecophilosophy (Jonas 1966. Odling-Smee 1996. Wilson 1999) and technology (Bedau *et al.* 2010. Brenner *et al.* 2006. Gershenfield 2012. Langton 1988. 1996), the thesis contemplates autopoietic-extended design as biologically and technologically generative. Common ground realized through interdisciplinary collaboration and complexity theory (Bird 2003. Bragg 2013. de Duve 2002. Fenwick *et al.* 2011. Langton 1988. Mason 2008a. b) is then mediated by non-linear data flows (Gibson 1986) and pervasive computation where:

A complex system is self-modifying in constant dialogue with other systems. Its many components are always alive, always interacting creatively with parts directly around them. These interactions form patterns all by themselves. They do not organize according to some sort of externally imposed blueprint or governing system. Complexity theorists describe such systems as autopoietic governing systems (Fenwick *et al.* 2011 26).

Importantly, sourcing complexity is consistent with autopoietic-extended design learning — students, tutors, education, technology, AI, and living environments can cultivate input/output flows inviting complexity’s unplanned contributions to thinking and design (Bayne 2010. Clark 2008a. Davis 2009. Fenwick *et al.* 2011. Gibson 1986. Mason 2008a. b. Maturana & Varela 1980. Thompson 2007). Such joinery makes possible autopoietic domains for studying non-linear data touching metabolic systems, intelligence, and machines and architecture. The possibility of students taking account of complex biological and environmental systems for

design implementation instantiates learning queries by asking what can architecture learn from nature? Christopher Langton suggests that:

The most surprising lesson we have learned from simulating complex physical systems on computers is that *complex behavior need not have complex roots*. Indeed, tremendously interesting and beguilingly complex behavior can emerge from collections of *extremely* simple components (Langton 1988 40 original emphasis).

Complex behavior in biomimetic robotics (drones, self-driving cars, machine vision) has demonstrated this point in experimentation that could be applied, adapted, or extrapolated to metabolic buildings (Markoff 2014a. Rieffel *et al.* 2013. Webb & Consi 2001). Interestingly, in reference to the gamification discussions (McGonigal 2011. Pew Internet 2013) (Sections 1.7, 7.2), Rieffel *et al.* used a game-engine (physics simulator) "because of its ability to model complex three-dimensional soft bodies" (2013 145). Keeping in mind off-the-shelf physics simulation for modeling and L-systems for biological generation (Chapter 5. 5.4), I return to Langton in relation to types of behavior and generation that I see holding potential for evolving biogenerative architecture:

A different approach to the study of nonlinear systems involves the inverse of analysis: *synthesis*. Rather than start with the behavior of interest and attempt to analyze it into its constituent parts, we start with constituent parts and put them together in the attempt to *synthesize* the behavior of interest. . . . Life is a kind of behavior, not a kind of stuff (Langton 1988 41 original emphasis).

Autopoietic-extended design attempts to *synthesize* and decode "constituent parts" as part of its generative epistemology realized through in-field observation and technological data sourcing.

Architecture analyzed first in Langton's sense of "a kind of behavior" or environmental action, encourages development of research *behavioral protocols* or even ways-of-being, as well as ways-of-seeing demonstrated by Rieffel *et al.* (2013). The lesson from Langton (1988 41) is then: "we start with constituent parts and put them together in the attempt to *synthesize* the behavior of interest" and thereby define system performance. For example, from the "Seedpod Data & Morphology" Student Handbook demonstration (Fig 29, p278), the flight behavior of winged seedpod is technologically traceable (and/or predictable) from the spirals of differing sine-wave frequencies, pitch, and intensity phenomenologically performed when the winged-seed detaches from the parent tree (See also Chapter 7. 7.5). Those flight patterns, in a long

design process, contributed to the realization that the lesson's bridge spirals need not be regular or even of the same frequency to enact structural stiffness. The phenomenologically resulting sine curves then helped "*synthesize* the behavior of interest" (Langton 1988) for "constituent parts" of the bridge.

"Constituent parts," along with autopoietic unities, consequently help organize investigation and visualization into what metabolically enhanced design performance might be. Richard Coyne's (2010) ideas of tuning become relevant in the context of in-field, smartphone mediated occupation and research. In Coyne's hypothesis of tuning, users and environments are synced, mediated, or *tuned* in the context of technological adjustments necessary as design, communication, and/or habitation actions. Coyne's premise may be engaged here when students using digital equipment, *tune* research, behavior, equipment, and environments in order to investigate nature and thereby attune themselves to the resulting data feedback (Coyne 2010. Langton 1988). In this sense urban or wild *tuning-in* becomes programmatically deployable in autopoietic-extended design and beneficial to m-learning smartphone data input.

Langton's (1988) *ALife* complexity, Bayne's (2008) uncanny pedagogy, Coyne's (2010) tuning, and Fenwick's (2011) *slippery* pedagogy are then all programmatically related to Barnett's (2007) discussion of risk in learning understood here as a ground-up pedagogical foundation. Furthermore complexity, *uncanny*, and *slippery* risk may be conceptualized as mutually in-play between students deploying the OS scaffolds to technologically source data from nature. I'm thus seizing on experimental educational theory to testify for (and test), new pedagogy taking account of complexity's role in design research, learning, and teaching when operative through autopoietic-extended design (Barnett 2007. Fenwick *et al.* 2011. Mason 2008a. b). For example, the citation below comes from the field of ecology but is a basic tenet, largely ignored I think, in design teaching:

We need to teach that being in the environment is, and always has been at the heart of being at all, and that both artistic and scientific endeavor are expressions of that dialogue. Very few environmental [or architectural] educators have engaged directly with this idea (Stables & Scott 152).

This is a point Sullivan (1979. 1999) emphasized for architectural education highlighted in Chapter 4. Below Weinstock captures similar pedagogical intentions:

The modeling and analysis of plant systems permits a new understanding of the emergent behavior, component hierarchies, and adaptive strategies of biological

structures, and permits the exploration of the mechanical performance of growth under stress (Weinstock 2006a 29).

I am not suggesting design learning collaborate with ecology or biology the way conservation or science would formalize. Instead, I situate nature as a nondualistic learning partner capable of reorienting architecture toward environmental input and bioremedial output by introducing academic design methods to activate first-hand, experiential data relevant to sustainability, morphology, materiality, and intelligence. But, in my thesis, this is only achievable with a highly technological framework for hybridizing metabolism with AI, living technology, and computational simulation.

The intention is to implement basic ontological research procedures and produce insight backed with collateral technology. For example, “In the educational uptake of complexity theory, what is emphasized are the flows and relations among things — not the things themselves” (Fenwick *et al.* 2011 21). Reorienting design research to metabolic “flows and relations” opens processes to biological functions giving designers opportunity to establish new research practices consistent with breakthroughs in synthetic biology and living technology. In this frame the process of being united through cognition and technology with the environment is itself an educational (autopoietic) domain — a flow (Gibson 1986 227) — with knowledge construction influencing ways of practicing design.

We may then analyze these data-rich learning domains for attributes of nature to be extrapolated to building materials, performance, or systems. And, we may cultivate the domains so that retrieved data will potentially inform or instill metabolic intelligence or logic when transferred to design — in this manner emergence is cultivated partly by readying students to deal with unfamiliar data from nature. Investigating and integrating natural and technological systems then brings to research, idea cultivation capable of translating functions from biological domains into design prototyping, a process Weinstock and Menges encapsulate:

What is needed is an approach to design that strongly integrates analytical and generative methods. Analysis is of central importance to the entire generative process not only in revealing behavioral and self-organizational tendencies, but also in the assessing and designing spatial-environmental modulation capacity (Weinstock & Menges 2006 63).

Analysis passing through autopoietic-extended design is then one answer to Weinstock and Menges's call for cross-domain “modulation” that “strongly integrates analytical and

generative methods" (Weinstock & Menges 2006 63). In the process of analyzing coded and decoded objects, living organisms, inert matter, and natural forces — in the context of social landscapes — interpretation relies on cognizing morphological form and performative behavioral data (Langton 1988 41). Complexity, in this setting nourishes cognitive extension through massive raw data flows for what Mason (2008a 5) calls "critical mass." In turn, through increased data feeds idea-rich information for visualizations and prototyping may be reckoned as pedagogically cultivated emergence.

Alerted to design analysis through complexity, students set their own experimental practices to nurture project experimentation (Barnett 2007. Bayne 2008. Gee 2007). Here from Mark Mason's "Complexity Theory and the Philosophy of Education" we hear:

Complexity theory's notion of emergence implies that, given a significant degree of complexity in a particular environment, or critical mass, new properties and behaviors emerge that are not contained in the essence of the constituent elements, or able to be predicted from a knowledge of initial conditions. These concepts of emergent phenomena form a critical mass, associate with notions of *lock-in*, *path dependence*, and *internal momentum*, contribute to an understanding of continuity and change what has not hitherto been readily available in other theories of or perspectives on change (Mason 2008a 5 original emphasis).

Mason describes emergent phenomena as including notions of *lock-in*, *path dependence*, and *internal momentum*. The results of those processes sometimes initiates unexpected feedback and "internal momentum" (Mason 2008a 5) as phenomenological learning:

Some would call learning the very dynamic of emergence in complex systems. Learning also could be the sudden jumps in the system's phase states, its transformations, as it experiences disturbances and internal fluctuations that can become amplified. Cognition occurs in the new possibilities that are always opening for unpredictable shared actions (Fenwick *et al.* 2011 29).

As task oriented, the above dovetails with concepts of autopoietic organization Maturana and Varela acknowledge in "transformations and destruction" and the "endless turnover of components under conditions of continuous perturbations and compensation of perturbations" (Maturana & Varela 1980 79). For example, in the introduction to *Autopoiesis and Cognition* they state: "knowledge always implies a concrete or conceptual action in some

domain," and all autopoietic domains undergo "deformations" and "perturbations" (Maturana & Varela 1980 xxii & 79). Fenwick *et al.* too, considers knowledge vis-à-vis education in complexity-rich, domain-defined cognition or physical "object" relationships:

In complexity terms, knowledge and learning are understood as continuous invention and exploration, produced through relations among consciousness, identity, action, and interaction, objects and structural dynamics. . . . Cognition occurs in the possibility for unpredictable shared action. Knowledge is not understood as an autonomous collection of concepts separate from the system in which these emerge. . . . Knowledge, learning, and teaching cannot be contained in any one element or dimension of a system, as they are constantly emerging and spilling into other systems (Fenwick *et al.* 2011 28).

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From the above view of complexity/knowledge, autopoietic-extended design can be cultivated to support specialized design research studios with concerns addressing morphology, metabolism, and bioremediation. Complexity theory with its roll-of-the-dice data flow, then supercharges in-field educational experimentation with:

. . . concept[s] of open, dynamic systems, embedded within and partly constituting each other, while at the same time maintaining their own coherence, allows for different ways of thinking about context, and provides a rationale for the investigation of individuals, difference, and specificity. By focusing on the interactions, rather than on static categories, complexity theory also makes it possible to consider different aspects of process (Mason 2008a 12).

Following Mason's "different aspects of process" into case studies or research, frames complexity to affect integration and affordances/affinities (Gibson 1986) aiding our sourcing and interpretation of non-linear data. "Different aspects of process" then furthers the reach of extended cognition tuning the anchorage of architecture in nature. Subsequent processing and filtering of raw data is then student transformed into information feeding from experience, observation and smartphone-aided design development. The "tuning of place," organisms, and technology is then in Coyne's sense "a set of practices by which people use devices, willfully or unwittingly, to influence their interactions with one another in places" (2010 xvi). Thereafter, autopoietic-extended design becomes an OS messenger shuttling input/output between the student and the environment as both constructed and constructing dialectic (Luhmann 2000), manifested in performative, generative design responses.

Reflecting on the previously discussed experiments investigating frog-constructed reality (Chapter 3. 3.1), I find potential for unfiltered flows of data to enrich insight and recognition in each student's construction of design through their own behavior and subjective interpretation of reality/nature (Lettvin *et al.* 1959). Maturana and Varela pose the foundational question for such an OS procedure:

Given a dynamic system what relations should I observe between its concrete components to determine whether or not they participate in processes that make a living system? (Maturana & Varela 1980 114).

At this point, where students are constructing design visions, autopoietic-extended design supplies them with minimal requirements for identifying life systems (Maturana & Varela 1980). Balancing metabolic function, program, and the use of technology, the OS provides support (via guidelines, how-to-examples, apps, tutor commentary, texts, and social media communications) theoretically sustained by Clark's (2008a) accounting of cognition-to-environment processes in parallel with Di Paolo's (2005) and Weber and Varela's (2002) adaptations for autopoietic sense-making.

The Student Handbook (Appendix 1) then illustrates how coupling smartphones and apps to investigative learning processes using autopoietic-extended design provides students with examples of decoding processes (i.e. the seedpod exercise Fig 29, p278) manifested in objects, urbanisms, and nature and reasoned through Clark's words:

The human mind, if it is to be the physical organ of human reason, simply cannot be seen as bound and restricted by the biological skinbag. . . The mind is just less and less in the head. . . . If we do not always see this . . . that is because we are in the grip of a simple prejudice: the prejudice that whatever matters about *my* mind must depend solely on what goes on inside . . . the ancient fortress of skin and skull. This fortress has been built to be breached; it is a structure whose virtue lies in part in its capacity to delicately gear its activities in order to be collaborative with external, nonbiological sources of order to better solve the problems of survival and reproduction. . . . For what is special about human brains, and what best explains the distinctive features of human intelligence, is precisely their ability to enter into deep and complex relationships with nonbiological constructs, props, and aids (Clark 2003 4-5 original emphasis).

Clark (2003. 2008a. 2013a) moved past binaries of mind/body and mind/nature to articulate new fields of cognition-to-environment operation. Autopoietic-extended design activates his theory in design domains supporting students searching new perspectives on intelligent and metabolic forms and organisms for application to building performance and morphology. D'Arcy Thompson said in 1917: "In a newer language we might call the form of an organism [architecture] an 'event in space-time' and not merely a 'configuration in space'" (Thompson 1961/1917 283). The "event in space-time" reflected in Clark and Thompson's words, and diverted to autopoietic-extended design, is itself an autopoietic *unity* (student deployable) whose feedback I recycle to support experimental metabolic and intelligent generative architecture by next looking to Clark's discussion of cognition in the environment.

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Chapter 7 • Andy Clark: Cognition Leaks

In “Re-Inventing Ourselves: The Plasticity of Embodiment, Sensing, and Mind,” (2007a) Clark sets out:

The notion of human enhancement suggests an image of the embodied and reasoning agent as literally extended or augmented, rather than the more conservative image of a standard (non-enhanced) agent using a tool via some new interface (Clark 2007a).

Clark's earlier mapping of tool augmentation and prosthetics in *Natural-Born Cyborgs* (Clark 2003) territorialized big data and cellphone mobility as cognitive enhancement before smartphones made their 2007 debate. And, as the above quotation asserts, he saw enhancement and environmental collaboration, not discrete tool-to-task relationships. From “Re-Inventing Ourselves,” I route his insight as pertinent to learning involving technologically sourced data augmentation and methods now deliverable by smartphones and networks.

Conscious and subconscious recognition, distinction, selection, and prediction are active components of metabolic animal (particularly human) insight and environmental occupation and navigation — they are phenomenological thought and action-generating devices setting the ability to see in a rock, for example, the performance of a hammer (Herrmann 1984) or, to predict the trajectory of a predator, and avoid it. Such performances in extended cognition surveying nature/objects are then partially accounted for by extended phenotypes expressed in animal constructions (Clark 2005. Dawkins 1982. Hansell 2005. Turner 2000. Weber *et al.* 2013). Additionally, Clark postulates prediction as a function, emphasizing its critical role in cognitive operations (Clark 2012. 2013. 2013a). The quote below from Maturana is then germane since it acknowledges the role of prediction in autopoiesis:

Each internal state requires that certain conditions (interactions with the environment) be satisfied in order to proceed to the next state. Thus, the circular organization implies the prediction that an interaction that took place once will take place again. If this does not happen the system disintegrates; if the predicted interaction does take place, the system maintains its integrity (identity with respect to the observer) and enters into a new prediction. In a continuously changing environment these predictions can only be successful if the environment does not change in that which is predicted. Accordingly, the predictions implied in the organization of the living system are not predictions of particular events, but of classes of interactions. Every interaction is a particular interaction, but every prediction is a prediction of a class of interactions that is defined

by those features of its elements that will allow the living system to retain its circular organization after the interaction, and thus, to interact again. This makes living systems inferential systems and their domain of interactions a cognitive domain (Maturana & Varela 1980 10).

Finding autopoiesis and extended cognition hospitable to theoretical agent-to-environment design operations — including prediction — supports generative strategies for recognition and distinction of metabolic components integrated into autopoietic-extended design functions (Clark 2013. Di Paolo 2008. 2010). Then, through autopoietic-extended design, students can plan, organize, and implement project research taking cues from the Student Handbook's (Appendix 1) lessons exemplified by:

- 1) Android & iPhone drawing apps (Fig 1, p29).
- 2) Leaf Investigation (Fig 2, p44).
- 3) Leaf Morphology (Fig 3, p45).
- 4) L-Systems and Generative BioAlgorithms (Fig 10, p88).
- 5) Tracking and GPS locational networking of research specimens/sites (Fig 11, p93).
- 6) Seedpod Data & Morphology (Fig 29, p278).
- 7) Mobile Video, Distribution & App Production (Fig 30, p279).

The Handbook guides on-site design data sourcing that may be instigated through biomimetic and technological observation resulting in ideas supporting exploration of genotype/phenotype expression (Langton 1988) as architectural extended phenotypes (Dawkins 1982. Hansell 2005. Odling-Smee 1996. Turner 2000). Generative strategies substantiate the view that architecture in functional, performative, and ecological terms is accountable to nature through technology when seeking metabolic functions addressed to ecological self-maintenance. In this accounting, architecture is culpable for its past inattention to, and lack of, ecological integration and bioremediating intelligence.

The lack of ecological research for the metabolic performance of buildings where biological integration is programmatically studied may be contrasted to high levels of research in bio-inspired computation (Floreano & Mattiussi 2008) or biorobotics (Adamatzky 2013. Montebelli 2013. Rieffel *et al* 2013. Webb 1996. 2009). Views and pathways for experimental metabolic architecture are both under-theorized and pedagogically scarce (Armstrong 2010. 2011. 2012. Menges 2006. Spiller 2009. Weinstock 2006a). In this setting, autopoiesis (Maturana & Varela 1980) plugs into extended cognition to activate biological criteria in order

to help students distinguish between animate and inanimate organisms at levels usually employed outside of design (Jonas 1966. Odling-Smee 1996).

Asking what is alive and what is not, and following the resulting implications of intelligence in the seriously asked, if uncanny question, Can buildings think? spotlights a metabolic context new to architectural research and dialectical argument. Thereafter, in applying attributes from cognitive prediction (Clark 2013. 2013a) and recognition/sense-making to design visualization via autopoietic-extended design, new infrastructural and material performance may be speculated on, experimented with, and prototyped.

For this line of thinking, as Douglas Hofstadter maintained for AI, "cognition is recognition" (Somers 2013) and recognition is essential to intelligence of any kind. Autopoietic-extended design supports researching agent intelligence, non-conscious sense-making, and AI in its OS use of recognition (Di Paolo 2008. 2010) and prediction (Clark 2012. 2013. 2013a). Along with subjective student choices and interpretation of data, the OS helps formulate how programmable and technological input for design, feedbacks to production. It thereby alerts students to the task of nurturing generative recursion for design ideas as compatible with biogenerative computation and fabrication. As Varela states: "cognition is action about what is missing" (Varela 1997 85).

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Natural-Born Cyborgs was published four years before the 2007 introduction of the iPhone — the generally agreed marker where limited feature-phones were challenged by smartphones. Statistics in 2013 show smartphones dominating usage trends in the UK and US (Dutton 2013. Pew Internet 2013). Smartphone growth notwithstanding, in his 2003 book Clark correctly observed the mistake of cyborgian prosthetics and the error in the idea of body/machine penetration (Haraway 1990). Clark warns:

Perhaps, then, it is only our metabolically based obsession with our own [bodies] that has warped the popular image of the cyborg into that of a heavily electronically penetrated human body: a body dramatically transformed by prostheses, by neural implants, enhanced perceptual systems, and the full line of Terminator fashion accessories. The mistake — and it is a familiar one — was to assume that the most profound mergers and intimacies must always involve literal penetrations of the [body] (Clark 2003 28).

Clark recognized an important cultural demarcation freeing the user from the shadows of cyborgian implants and large body-worn tech appendages by identifying enhancement first

and foremost as cognitive and/or environmentally activated. This, I see as a generally underestimated demarcation with ongoing consequences involving Turingesque questions of machine intelligence (Chapter 5) when biology, metabolism, and AI/synthetic biology are factored in as components of generative architecture.

Recognized in the pedagogical context of this thesis, technological embeddedness not only reveals impact witnessed in technology-to-student mediation, but in the virtual transformation of the university, and architectural space in general. More specific to design learning concerns, in clarifying cyborgian implications vis-à-vis cognition-to-technology-to-cognition, Clark's work opens data-to-cognition pathways for autopoietic-extended design to question and test what m-learning technologies could be widely sourced for data streaming, inter-class communications, and app appropriateness (Appendix 1).

Clark's theory and explanatory examples reach through environmental and technological affordances (Gibson 1986. Wells 2002) to survey methods for recognizing objects, environments, phenomena, and organisms through extended cognition as "agent-world circuits" (Clark 2007a 4). In this sense, technological-dystopian nature, formerly manifested in cyborgian appendages (Clark 1997. 2003. Haraway 1990) is radically reinterpreted as minimally disruptive data flows witnessed today, for example, in Google Glass and smartphone addiction.

By decoding organisms/objects and sourcing environmental and living data and phenomena, autopoietic-extended design shows itself as procedurally, cognitively, and educationally engaged. The OS is capable of deploying both autopoiesis and extended cognition in search of metabolic and morphological attributes for designers' striving to engage their work in bioremedial actions (Figs 1, p29. 2, p44. 3, p45. 11, p93. 29, p278. 30, p279 & Appendix 1). Di Paolo concludes "Robotics Inspired in the Organism" with a relevant biomimetic observation: "we should aspire" he suggests, "to imitate the principles of the biological world (as opposed to imitating only what we are interested in)" (Di Paolo 2010 157).

So, while use of smartphones won't alone affect design education as pervasively as would an understanding and implementation of Clark's "self re-configuration" (below). There are good reasons why technology as a collaboratively "embodied agent" in an enactive program (Varela *et al.* 1992) such as autopoietic-extended design (Appendix 1), should figure large in reconceptualizing architectural-learning performance — since the self-configured agent/student is:

... the "profoundly embodied agent" [with] a means of marking the philosophical and scientific importance of our potential for repeated and literal episodes of self-reconfiguration [learning/design] (Clark 2007a).

Self-reconfiguration is here read as a bioremedial research program helping to organize *students + technology + environment* as autopoietic unities working in the domains of metabolic and biogenerative architecture. This programming (pedagogically assigning roles to cultivate actions) is ontological in the realm of architecture as an extension of human thinking and an aspect of extended phenotypic materialization in nature (Dawkins 1982. Hansell 2005. Weber *et al.* 2013). Self-reconfiguration is therefore considered imbuing metabolic potential for architecture in domains of environmental crisis (Clark 2008a. Lewontin 1983. Varela *et al.* 1992).

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7.1 • Reconfiguring Design Learning

From the above, Clark's "self-reconfiguration" holds insights for students to construct knowledge embodying insight into metabolic functions and architectural extended phenotypes for application in learning and building (Fenwick *et al.* 2011. Jonas 1966. Maturana & Varela 1980). Autopoietic-extended design's ongoing engagement with generative architecture, autopoiesis, and extended cognition therein cultivates ideas to evolve research methods transitioning design sense-making to place-, material-, or thing-making (Di Paolo 2005. Weber & Varela 2002):

Modeling growth processes that are sensitive to system-extrinsic influences and negotiated with system-intrinsic organizational information and related features hold great potential with respect to evolving buildings. . . . incorporat[ing] ecological organization and relations. Ecology is the study of the relation of organism to their hosting environment, which can be studied at various levels ranging from the individual organism to populations, communities of species, ecosystems, and finally the biosphere (Hensel 2006 15).

Merging "growth processes," ecology, and design, I expect autopoietic-extended design to be: "literal episodes of [learning] re-configuration" (Clark 2007a) bolstering class participation, design, and productions — what Maturana calls "classes of interactions" (Maturana & Varela 1980 10). Within such a framework the education environment may be recognized as contingent with Clark's "profoundly embodied agent" (Clark 2007a). It may be analogously mapped for students learning territorial and evolutionary protocols typified in videogame strategy (Chapter 1. 1.7) I define as: *Go there, Do this, Get that* (Brooks 2001. Gee 2007. Kirkpatrick 2011. Speed 2011). The tie-in links both "classes of interactions" and

videogame play through research assignments involving smartphone/apps used for location and data mapping (*go there*), documenting observed natural attributes (*do this*), and translating into a design (*get that*).

For almost two decades Clark has been compounding, intensifying, aggregating, and surveying research from objects and environments while simultaneously investigating phenomenological data decoding. For design learning, his examples are appropriate to methodology, organization, and observation while being hospitable to extrapolations for systems, materials, and design performance (Bayne 2008. 2010. Fenwick *et al.* 2011. Mason 2008a). For example in 2003's *Natural Born Cyborgs*, Clark describes the slime tracks slugs leave in a garden as "glistening, sticky signatures. . . . These trails record, reveal, and simultaneously help structure slug activity" (2003 143). He then discussed the "glimmering" trails in parallel with "our own electronic trails, laid down as we access data, buy online, and move physically through a world of intercommunicating information appliances" (2003 143). For analogy, "sticky signatures" are considered extended phenotypes available to data mining (Clark 2001b. Dawkins 1982). This genre of biochemical traces illustrates metabolic data in the position for interpreting design research involving digital surveillance, tracking, (Fig 11, p93) and mapping (Speed 2011).

After a brief description of the mucus trail's molecular components, Clark cites the pheromone tracks of the Argentine ant in order to discuss chemical signatures as feedback mechanisms and self-organizing trails (networks) that analogously relate to algorithms (Clark 2003). Clark is leading toward an AI example of Amazon.com's use of shoppers' digital traces to compile customized promotional information as feedback — insight dependent on AI rooted in theories pioneered by Turing (1948) called "*genetical or evolutionary search*" (Teuscher 2004 500 original emphasis).

For Clark the Amazon.com semblance to slug trails foreshadowed research and prediction for networks he discussed in recent work where data trails feed predictive systems (Clark 2012. 2013. 2013a). Almost contemporaneously, similar research fixed on urbanisms has extended to urban traffic in works such as "Living in Living Cities" (Gershenson 2013. Greenberg & Jeronimidis 2013). My point is that observation of nature and culture reveals data harnessed by visualization to generate ideas resulting, as Clark (and Maturana and Varela) articulate, in predictive cognition (Clark 2013. 2013a. Maturana & Varela 1980 10).

Related, student research requires data acquired and rationalized for predictive cognition to output and test experience, observations, and knowledge constructing design. Clark questions not only whether cognitive extension is operational, but also which parts are active and how they are activated to filter data. In the above Amazon/slug example, data is

extrapolated via experience and slug or Amazon research, so that through prediction, ideas may be weighted and hypothesized and prototyped (Clark 2007b. 2008a. 2013. Di Paolo 2008. 2010. Malafouris, & Renfrew 2010. Menary 2010). It is in unfolding such research, that procedures from extended cognition case studies may be read, extrapolated from for architecture, and overlaid into design formulations.

Following Clark's research, I suggest testing methods for design learning. I hold that hybridized with autopoiesis, his theory repositions traditional ways of thinking about architectural knowledge by reconceptualizing spatial/environmental occupation (Malafouris & Renfrew 2010). Clark's line of thinking, if routed through autopoiesis pairs operational procedures (extended cognition) with Maturana and Varela's (1980 100) "three phenomena: . . . replication, copy, and self-reproduct[ion]." All three phenomena are active in extended cognition when vivified through students engaged in generating ideas, perceptions, and visualizations. Herein, idea production and reproduction in the frame of Clark's agent-to-world (student-to-world) can be likened to:

A system which successively generates unities different from itself, but in principle identical to each other [ideas], and with organization which the systems determines in the process of their production, is a reproductive system (Maturana & Varela 1980 100).

The starting unities for the above are here comprised of *student + technology + environment*. Idea reproduction with variation within an autopoietic unity/domain powers cognition (Clark 2013) with evolutionary ability to realize and adapt design ideas recursively (Dawkins 1982. Di Paolo 2005. 2010). Related to the above quotation, Maturana and Varela explain:

In living systems presently known on earth, autopoiesis and reproduction are directly coupled, and hence, these systems are truly self-reproducing systems. . . . Self-reproduction [of ideas] is a form of autopoiesis (Maturana & Varela 1980 101).

If Clark (2013a) negotiates cognition, embodiment, and environment, Maturana and Varela (1980) negotiated biological systems and environment. Clark and Maturana and Varela have dealt with biologically generated living phenomena in the form of ideas, inspiration, and perception. Below we read Maturana and Varela's concerns emerging in a discussion excerpted from Cary Wolfe:

“Our intention is to bypass entirely [the] logical geography of inner versus outer by studying cognition not as recovery or projection but as embodied action.” (172) — “embodied” because cognition depends on the “individual sensorimotor capacities” of the embodier in situ, and “active” (or “enactive”) because the cognitive structures that guide perception and action. . . . The definition of “embodiment,” then, is a self-referential, self-organizing, and nonrepresentational system whose modes of emergence are made possible by the history of structural coupling (Wolfe 1998 60-61 Quoting Maturana & Varela 1987).

Here we encounter a concept of “embodiment” from Maturana and Varela ideal for folding into Clark’s extended cognition. Wolfe’s perspective also preexists for Clark, and playfully too: “Cognition leaks out into the body and world” (2007b 164). Clark’s leaking-cognition metaphor (2007b) flows multidirectional — non-compass — it’s receptive to systemic autopoietic processes for recognizing metabolism and intelligence in other systems (Di Paolo 2005. Maturana & Varela 1980. Weber & Varela 2002). As Maturana wrote in the “Introduction” to *Autopoiesis and Cognition: “Living systems are cognitive systems, and living as a process is process of cognition”* (Maturana & Varela 1980 13 original emphasis). And, while non-cognitive living systems are not uncommon, and hold important implications for design, I take his point.

Extended cognition (Clark 2008a) is an existing agent-factor in the landscape of design perception. It is part of nature, perhaps a force of nature (Nagel 2012), and therefore perceptually and generatively critical to metabolic architecture. As a preexisting system it prompts me to:

- 1) Consider how in an autopoietic-extended design OS, embedded and emergent metabolic intelligence in nature can be nurtured for design goals.
- 2) How an autopoietic protocol within an OS could become effective for extended cognition to address metabolic systems and data as differently reproducible for material integration into bioremedial, generative architecture.

Placing the above concerns in a context oriented to objects and things, we hear Malafouris and Renfrew from *The Cognitive Life of Things* (Chapter 5):

Things have a cognitive life because intelligence exists primarily as an enactive relation between and among people and things, not as a within-intracranial representation. . . . In that sense, the cognitive life of things denotes the mode of being of the “active mind”

which is to be contrasted with “objecthood” as the mode of being of the “passive mind.” The way to understand this is by starting to see materials, objects, and artifacts as graduations or ontological moments in the cognitive life of things (Malafouris & Renfrew 2010 4-5).

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The extended cognition challenge as hybridized here for architecture, lies in hosting a biological methodology — autopoietic theory — and then tasking the hybrid to collaboratively source phenomena and data at levels visually and technologically usable to students. This OS tasking provides alternative routes to data and visualizations feeding and organizing a nuanced picture of nature observed by balancing direct observation with technologically rich (sometimes unique) Internet, archival, and scientific data functioning through Clark’s (2007) “agent-world circuits.” *Agent-world circuits* then feed autopoietic unities in environments meeting extended cognition as “larger hybrid wholes, comprising biological and non-biological elements” (Clark 2007b 168).

With Clark’s *agent-world circuitry* in mind for an autopoietic-extended design substrate, I introduced Maturana and Varela’s *Autopoiesis* (1980) into extended cognition to activate both a mobile design OS and an analogue learning system referenced to morphology via Sullivan’s *System* (Chapter 4). I stress the hybridization process was patterned on *folding-in* that does not thoroughly blend, nor thoroughly obscure individual properties of either autopoiesis or extended cognition. The resulting OS hybrid is charged on the one hand with outlining the potential structure and its protocols for a digital app, while on the other hand, it functions as a student and tutor procedural for research and/or class programs (Appendices 1. 2). That program notably redefines (dualism, autopoiesis, and cognitive continuity) in a continuum between sense-making, technology, and nature. Niklas Luhmann relates:

[T]raditional attribution of cognition to “man” has been done away with. It is clear here, if anywhere, that “constructivism” is a completely new theory of knowledge, a post-humanist one. This is not intended maliciously but only to make clear that the concept of “man” . . . as designation for the bearer and guarantor of the unity of knowledge, must be renounced. The reality of cognition is to be found in the current operations of the various autopoietic systems. The unity of a structure of cognition (or the “system” in the sense of transcendental theory) can only lie in the unity of an autopoietic system which reproduces itself with its boundaries, its structures, and its elements (Luhmann 1990a 72).

I listen to Luhmann's constructivism grounded in autopoiesis (nature, cognition, society) and follow it by developing methods to select and adapt raw data as research input/output in "various autopoietic systems" (Di Paolo 2005. Luhmann 1990a. Maturana & Varela 1980. Weber & Varela 2002). Luhmann articulates methods for doing this based on:

- 1) "Distinctions" as "instruments of cognition" (Luhmann 1990a 76).
- 2) "The concept of observation" as an "empirical operation" (Luhmann 1990a 77).
- 3) Communication "when an observer is able . . . to distinguish between the act of communication and information, that is, to understand communicative acts as the conveying of information (and not simply as behavior)" (Luhmann 1990a 79).

In that context nature may be scrutinized beyond transcendent inspiration by privileging the ontological roles of biological models and data over a priori conceptualizations. As we have seen, Luhmann's "concept of 'man' . . . as designation for the bearer and guarantor of the unity of knowledge, must be renounced," is closely related to Gosden's (2010 39). "concept of mind has outlived its usefulness" (Chapter 6. 6.1). Both Luhmann and Gosden proffer visions and arguments useful to my view of how design research for architectural intelligence and metabolism may be fused into OS and university programming (Fenwick *et al.* 2011. Gosden 2010. Luhmann 1990a). Those visions now help cultivate cognitive and emergent autopoietic-extended design unities for nurturing environmental and technological feedback to inform the design. Clark points out:

What is really at issue, as far as the claims about cognitive extension are concerned, is which bits of the world make true . . . certain claims about a subject's here-and-now mental states or cognitive processing (Clark 2007b 171).

"Which bits," *which view*, or *which data* — sensory distinguishing — becomes an operational quest, what Luhmann isolated in saying:

. . . distinctions are codifications specific to cognition, which function independently of the environment (i.e. of stimuli), because there are not and cannot be any equivalents for them in the external world (Luhmann 1990a 76).

Deployed differently: distinctions and which bits of the world make *learning*? or which

bits of the world make *design*? are autopoietic-extended design precepts helping students organize. That organization is enacted in procedures and theories Clark's and Maturana and Varela's work cultivates, and I use here, as core features of autopoietic-extended design: they include conceptual realignment of nature (synthesis) for obtaining and visualizing natural data (Appendix 1) — these may come from observed/researched:

- 1) Non-human biocognition or sense-making (e.g. bacterial intelligence).
- 2) Plant/animal-based biomechatronics or living technology.
- 3) Scientific visualization (e.g. scanning electron microscopy).
- 4) Bioroboticlike hybridized facade and/or infrastructural systems.
- 5) Biomimetic extrapolation, sketching, and 3D in-field scanning.
- 6) Biohacking and bioengineering.
- 7) Distributed metabolic intelligence controlling building functions from embedded sensors.
- 8) Biochemical processes, e.g. photosynthesis integrated into structural materialization.

As touched upon earlier with the example of "biological-agent + stick" (Chapter 1. 2.0), Clark identifies an example of perception through an object (tools as circuits and interfaces meeting body, cognition, and environment):

... there suddenly seem to be two interfaces at play: the place where the stick meets the hand, and the place where the extended system "biological-agent + stick" meets the rest of the world (Clark 2007a).

I'm reconfiguring Clark's example of compound agency from "biological-agent + stick" to *biological-agent + smartphone* or *biological-agent + electron scanning microscope*. For autopoietic-extended design, Clark's agent + stick illustrates how students and smartphones may be coupled as machinic "new agent-tool interface[s]" (Clark 2007a). Framed within nature, student/smartphone circuits share metabolism, data, coupling/parity, and operational organization. Clark's "Re-Inventing Ourselves" (2007a) and "Curing Cognitive Hiccups" (2007b) prompt the cultivation of agents and circuits (students with smartphones, tablets, apps) programmatically interfacing design research as (*agent + smartphone + design program + environment*).

Student-circuitry then promotes environmental feedback, data flow, and niche construction to host extended phenotypes as realized constructions and production routes for

design prototyping (Dawkins 1982. Jonas 1966. Odling-Smee 1996. Odling-Smee *et al.* 2013). And, even while I am situating smartphones and apps as collaborative, without doubt pedagogies such as Sullivan's (1990) *A System* equally, if in analog form, construct learning around agents-in-circuits (Chapter 4). To comprehend *A System* as an interactive circuit when agent activated, we need only acknowledge that each drawing cell is sequentially leading to the next, and each sequentially referencing its predecessor in a process directed to form-finding (Fig 15, p157) between *System* and student.

Clark's theory operates through agents and circuits that establish territories around which autopoietic domains construct momentary virtual/cognitive borders akin to membranes; analogous to Maturana and Varela's (1980 10) "classes of interactions." Borders between living cell walls (membranes) or virtual/cognitive constructions (like thought bubbles in comicbooks) maintain unity-defining enclosures while leaving open possibilities of cross-wall porosity for transfer of matter. "Building Dwelling Thinking" ("Bauen Wohnen Denken") tells us:

A boundary is not that at which something stops but, as the Greeks recognized, the boundary is that from which something begins its essential unfolding (Heidegger 1993/1951 347-363).

Morphologically speaking, protein folds may be a graphic example here of design-dependent docking (interlocking shapes) for activating communications (Foldit 2008) by which interfacing borders engage metabolically. Porosity across a border/membrane then partially determines communication for what qualifies as intercellular communication (cross-talk) and metabolic comings and goings. Porosity as gate keeping thereby provides a prototype biological machinic (e.g. stomata in leaves) for biomimetic design involving synthetic life, living technology, and AI engaging architectural performance (Margulis 1999. Maturana & Varela 1980. Montebelli *et al.* 2013).

The benefit for students arises in the ability to cultivate organizational, observational, and technological data structures anchoring design insights and objects in order to view functions and attributes from plants, shells, leaves, skeletons, bacteria, street networks, infrastructural systems, trees, cities, etc. (Chapter 6) (Malafouris & Renfrew 2010). These subjects may be scrutinized through channels of science, software, computation, and design programs to reveal biomimetic performative narratives involving morphology and adaptivity (Fenwick *et al.* 2011. Hayles 1999). In the above scenario, students may come to terms with what Heidegger (1993 363) called "essential unfolding" and Jonas calls the "concept pair 'organism-environment:'"

From this original fact of life's having commerce with an environment we should exclude all premature suggestion of the duality of subject and object. The original condition is an environment contiguous with the organism: in this stage environment is nothing but the immediate surroundings with which the chemical interchanges of metabolism take place (Jonas 1966 102).

Jonas's sense of metabolic organisms (bodies), and Clark's (2003 4) "biological skinbag[s]" (p250) take on the same "contiguous" relationships in the environment that cells do in organisms — skin becomes the membrane interfacing living organisms/environments and both metabolic and inanimate nature. Helping students define design research (Hayles 2012) from such metabolic narratives thereby engages their observational and technological abilities to situate class briefs as participatory with nature and consistent with OS facilitated autopoietic-extended design. The construction of research through such methods is then a differently sustainable design practice, and differently opens to cultivation than through the vagaries of learning encountering restrictive partitions from mind/body, body/nature dualisms.

With a narratological, technological, and metabolic drive for understanding research potential, students may construct procedures in which they can organize, innovate, manage, and implement data as responsive to environmental and project needs in relation to their own data-enhanced experiential observations (Armstrong 2012. Hensel 2006. Spiller 2009. Weinstock 2006). A narrative (including graphic visualization) unfolded, drawn, or STL prototyped by the student is then integral with autopoietic-extended design research and communication. It promotes the transformation of data for conceptualizing and rationalizing before seeking to materialize project visualizations in fabrication and performance (Bayne 2008. Fenwick *et al.* 2011. Hayles 2013. Jonas 1966).

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7.2 • Parity Principle & Structural Coupling

To implement autopoietic-extended design in a dual-function scaffold for an OS and class protocol, I rely on autopoietic theory banding component functions such as unity, parity, and coupling to support the unfolding of metabolic attributes:

Whenever the conduct of two or more unities is such that there is a domain in which the conduct of each one is a function of the conduct of the other, it is said that they are coupled in that domain. Coupling arises as a result of the mutual modifications that

interacting unities undergo in the course of their interactions without loss of identity (Maturana & Varela 1980 107)

Similarly, a strong but nonexact process exists between autopoiesis and Clark's parity principle (Clark & Chalmers 1998. Clark 2008a. b) where object and environment communication is parallel to autopoietic domain interactions and structural coupling supporting student research:

If a process in the world works in a way that we should count as a cognitive process if it were done in the head, then we should count it as a cognitive process (Clark 2008b loc 73-74).

Applied to bacteria, for example, Clark's parity principle might read differently while maintaining fidelity to his equation:

If a process in the world works in a way that we should count as [*a sense-making*] process if it were done in [*a non-conscious organism*], then we should count it as a process [*of intelligence*] (Clark 2008b loc 73-74 bracketed italics inserted).

Extended cognition's parity principle overlaps with autopoietic structural coupling (Maturana & Varela 1980) providing a reading that could include a building with biological functions. Both theories participate in component unity, domain interactions, and metabolic sense-making exchanges (Di Paolo 2005. Weber & Varela 2002). And both theories have active roles via metabolism and cognition in, for example, what Lettvin *et al.* (1959) calls the construction of reality, and Luhmann (1990a) calls the constructing knowledge. Owen Flanagan identifies similar construction of reality in "neurophilosophy," saying "a person's actual character is a state of being [in nature], and thus not simply or only in the head" or for that matter in any particular object or organism (Flanagan 2011 55). Flanagan's statement leaves prospects of "a state of being" open to construction.

Autopoietic structural coupling (Maturana 2002 27) accounts for communication between cognitive agents, sensorimotor systems, unities, domains, and environments across membranes and bordered environments. Extended cognition's parity principle recognizes equivalence between cognitive acts performed, processed, or co-processed by agents engaging environments, objects, or phenomena (Clark 2008b loc 73-74). Fused or hybridized, structural coupling and the parity principle (coupling-parity) forge a single strong tool for autopoietic-extended design. Such a coupling-parity tool facilitates adaptation helping the student/user

recognize, decode, and equate metabolic and phenomenological attributes in differing categories or degrees of intelligence, say between attributes of a plant, bacterium, and animal. In this role, and in principle, it further addresses Turing's (1950 215) "something which ought to be described as thinking but which is very different from what a man does?" by recognizing multiple (cell, plant, animal, machine, algorithm) types of intelligence beyond the animal world.

Equating structural coupling with the parity principle becomes a prominent OS feature in autopoietic-extended design. Between the two, I find sufficient liberty for proceeding with hybridization. Hereafter:

... reproduction, processing of information [cognition], or internal hierarchical relations [cross-boundary communication] are described as fundamental constitutive features of the living organization ... (Maturana 1974 150).

... and, "living organization" is looked to here for nurturing generative architectural performance yet to be realized but under research. Ultimately, hybridization offers a working mechanism otherwise unavailable to design processes in either of the original theories (Clark 2008b. Di Paolo 2005. 2008. Maturana 1974. Maturana & Varela 1980). By selection, revised autopoietic functions, with their consequent extended cognitive roles in the environment, make ready autopoietic-extended design for the investigation of nature, metabolism, intelligence, and biocomputation side-by-side with (sometimes inside) student observation (Di Paolo 2005. Maturana & Varela 1980. Thompson 2007. Weber & Varela 2002)

Enabled, autopoietic-extended design then theoretically, organizationally, and programmatically supports field research with theory defining architecture as part of nature. It does so with technological- and observational-data acquisition integrated with student-to-environment, student-to-technology, and student-to-class communication. As a learning/research scaffold, autopoietic-extended design facilitates organizational and experiential design research — ideas to fabrication — as a continuum of thinking involving digital computation (Clark 2008a. Di Paolo 2005. 2008. Maturana & Varela 1980. Weber & Varela 2002) that then instigates and supports the generation of ideas from nature to cultivate metabolic architecture.

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7.3 • Adaptations to Autopoiesis

While *Autopoiesis: The Organization of the Living* (Maturana & Varela 1980) most fully targeted cellular biological systems (Thompson 2007 106), it also influenced fields such as cybernetics

(Clarke & Hansen 2009. Hayles 1999) and systems theory (Luhmann 1990a. 1996. Schumacher 2011). Maturana and Varela's own (1987) *Tree of Knowledge* looked to explain autopoiesis via biology for a popular audience; and Varela, Thompson, and Rosch (1992) framed autopoiesis in enaction modeled on Buddhism in *The Embodied Mind: Cognitive Science and Human Experience*.

Adaptations to autopoiesis (Maturana & Varela 1980), as it works within this thesis, primarily date from Weber and Varela's (2002) paper: "Life after Kant: Natural Purposes and the Autopoietic Foundations of Biological Individuality." But, Weber and Varela's seminal work prompted a further and critical insight, that autopoiesis required adaptivity (Di Paolo 2005. 2008. 2010) for implementation of sense-making. In subsequent iterations, adaptivity tasked the formality of the original theory with insights and constructs empowering sense-making as a mechanism for hybridizing autopoiesis with enactivism and extended cognition (Di Paolo 2008. 2010). In a profound theoretical injection, Di Paolo (2005) gave autopoiesis performative and methodological reach in the physical world — not just in its biological domains. Di Paolo's research (2005, 2008, 2010) set the stage for the type of hybridization I formulate for enacting metabolic and biogenerative design research and observation (Figs 6-10a, pp76-89). In sum, Weber and Varela (2002) and Di Paolo (2005) provided a strong reframing of Maturana and Varela's (1980) autopoiesis, capable of expansion into the realm of cognitive extension (Di Paolo 2010) and here, programmed for architecture through autopoietic-extended design.

I identify input/output used for design learning/research (Hayles 1999) in a role original autopoiesis denied: "Living systems, as physical autopoietic machines are purposeless [non-teleological] systems" (Maturana & Varela 1980 86). In defying the original theory in favor of evolved autopoiesis, the implementation of OS procedures for design has proceeded to testing in learning situations (Appendices 1. 2). Thereafter, if Weber and Varela (2002) set in motion corrective measures, Di Paolo (2005) critically expanded, articulated, and executed evolutionary adaptivity for autopoiesis facilitating sense-making and recognition as teleological necessities. In recognizing teleology, Di Paolo wrote:

What our story requires is . . . for the organism itself to be able to generate such norms [meaning, risk, comfort, recognition] . . . and to regulate its operations accordingly (to *evaluate* the situation) within the space of structural options that correspond to the conservation of autopoietic organization. This capability describes the property of *adaptivity* (Di Paolo 2008 14 original emphasis).

Di Paolo (2010) elaborated the adaptivity requirement two years later in, "Robotics Inspired in the Organism." In that paper he parallels an idea I have paired with Coyne's (2010)

concepts of "tuning" environments. Still, Di Paolo further asked: "what is life?" — in order to then evolve a discussion:

[W]e may speak of an organism's activities as directed towards an end, or of its morphology and physiology as serving a certain purpose, but in fact this is meant to capture regular correlations between an effect and its causes given a context of norms which is "tuned" — that is, brought into coordination — by some external process such as evolution and not internally generated by the organism itself (Di Paolo 2010 136).

As important as this statement is in accounting for teleonomy/teleological drive and, in my contention, enabling autopoiesis as a collaborator with extended cognition, there are points to clarify.

Di Paolo's (2010 136) above statement "[re-]tunes" the function of teleology with the need for environmental engagement, where Weber and Varela and then De Paolo tell us:

- 1) Inherent teleology accounts for non-conscious sense-making and homeostasis witnessed in bacteria and single cell life (Weber & Varela 2002).
- 2) Teleology and sense-making are subconscious or non-conscious phenomena (again, in bacteria for example) participatory in evolution, sense-making, or adaptivity (De Paolo 2005).

As a result, I highlight both Weber and Varela's (2002) and Di Paolo's (2005) contributions to autopoietic-extended design's activation of an agent's ability (again, in bacteria for example) to identify, recognize, and configure metabolic systems in nature for extrapolation to design (Di Paolo 2005. 2008. 2010). In a case with bacteria as agent, distinctively ontological properties relating to, Can buildings think? emerge when:

... an autopoietic system must be able to recognize ... the virtual tendencies that relate it as a whole to the potential loss of its own viability [performance in the environment] (Di Paolo 2008).

Therefore, if on the level of a Turing machine (1936), or on the composite level of a Google car, a building can think (biologically sense and control actions in an environment) and is autopoietic, then the building system requires sense-making abilities discussed above in order

to “relate it[self] as a whole to the potential loss of its own viability” (De Paolo 2008) An autopoietic building may thus be contemplated as having metabolic purpose.

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7.4 • Extended Phenotypes & Architecture

Clark's work (2001b. 2003. 2005. 2007a b. 2008a. 2012. 2013) analyzes environmental, biological, biorobotic, AI, and object interactions, including animal-built constructions (Dawkins 1982. Hansell 2005. Turner 2000. Weber *et al.* 2013). That analysis further considers tool making, object use (Malafouris & Renfrew 2010), and symbolic representation (writing and drawing) as theoretical precedents for generative architecture to engage autopoietic-extended design. To these usages:

... different senses in which the term tool is applied in human and animal biology, makes a distinction which incidentally but rightly includes all construction behavior. The distinction is between constructions that conform to the Dawkins (1982) concept of extended phenotype (a product of the animal's genotype, externally expressed), and those that result from a mental plan (Hansell 2005 125).

This section is then drawn from various sources and focused to reflect Clark's theories and use of extended phenotypes (Clark 2001b. 2008a). For example, how cricket burrows (2005), Feynman's papers (2008a xxv), robotics, (2003), or archaeology (2010) imbue his research with architectural relevance. Relevance that is multidisciplinary and nested like Russian dolls in narratives of process and nature (Jonas 1966). Having followed Clark (2010a) in parallel to archaeology (Chapter 6) (Malafouris & Renfrew 2010) and biomimetic structures (Dawkins 1982. Hansell 2005. Turner 2000), I think it safe to apply his theory to experimental research methods in biogenerative architecture. Therefore, in addition to Mike Hansell's (2005 194) above quotation, his more encompassing definition of extended phenotypes may be worth revisiting (p50).

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Clark explains extended cognition in which human-interfaced activities of writing, drawing, or building demonstrate cognitive engagement, sometimes these same examples illustrate extended phenotypes (Clark 2001. 2005. 2008a. Dawkins 1982. Hansell 2005. Luhmann 1990. 2000). His opening example from *Supersizing the Mind*, considers Richard Feynman's protesting to historian Charles Weiner that his (Feynman's) working notes *did not document* his thinking process, but were in fact, "thinking on paper" (2008a xxv). Below we hear one way of aligning

Feynman's statement through extended cognition — a quotation that correlates Feynman's insistence with Clark's explanation (and my A, B, C brackets):

The loop through pen and paper is part of the physical machinery responsible for the shape of the flow of thoughts and ideas [A] . . . It reliably and robustly provides a functionality which, were it provided by the goings-on in the head alone [B], we would have no hesitation in designating as part of the cognitive circuitry [C] (Clark 2008a xxv).

This variation of Clark's parity principle, examined from logic rooted in, if: $A = B$, and $B = C$, then $C = A$ posits a logical structure through which design analogy and methodology may be contemplated or computer programmed.

Clark hypothesizes the environment as part of cognition through which we may comprehend "self-engineering" looping cognition in the environment. By following "Beyond the Flesh: Some Lessons from a Mole Cricket" (2005) with *Supersizing the Mind* (2008a b) Clark traced discussion of mole crickets and animats (Turner 2000. Webb 1996) supported by the parity principle (coupling-parity). The 2005 paper investigated cricket and burrow relationships where, so to speak, the cricket hybridizes itself and its earthwork simultaneously in a physiological, genetic, and environmental task with cognitive implications of timing, response, and maintenance performed through an extended phenotype (Bennet-Clark 1987. Clark 2001b. 2008a. Dawkins 1982. Turner 2000. Webb 2009. Weber *et al.* 2013). The male cricket, by extending (amplifying) his mating call through his architectonic burrow, temporarily, yet metabolically engages the constructed world. Scott Turner describes:

Mole crickets accomplish this remarkable feat [sonic broadcast and ground vibration] by building singing burrows, which happen to incorporate many of the features that make horns such marvelous acoustic devices (Turner 2000 170).

In this case, extended cognition's circuitry includes the cricket's actions using natural but inanimate matter to construct a physical structure and instrument; presumably as genetically determined (Chapter 2. 2.3) as those of *Peromyscus* mice (Weber *et al.* 2013). The burrow is engaged cognitively and physiologically to aid genetic reproduction with sonic characteristics and acoustics matching those of a Klipsch horn (Turner 2000 171). Turner notes: "it would appear that these insects have hit upon the same solutions for boosting performance that musical instrument makers have" (Turner 2000 171). Importantly for an architectural analogy, we glimpse a species building for the purpose of survival (i.e. reproduction), by

constructing not a nest, but a machine, a sound amplifier involving gene-directed phenotypic performance in an architectural instrument employed to enhance cricket-mating calls. In this case the line of development moves from genotype to phenotype to extended phenotype (Dawkins 1999. Hansell 2005). The burrow illustrates intelligence coupled in extended phenotypes (object/constructions) via cognitive circuitry to become an enactive architecture (Dawkins 1982). Clark tells us:

It matters that we recognize the very large extent to which individual human thought and reason are not activities that occur solely in the brain . . . it drives home the degree to which environmental engineering is also self-engineering [autopoietic self-maintenance]. In building our physical and social worlds, we build (or rather, we massively reconfigure) our minds and our capacities of thought and reason (Clark 2008b loc 382).

Because Clark buttresses extended cognition with autopoieticlike "self-engineering," I interject a connection from Weber and Varela:

. . . autopoiesis proposes an understanding of the radical transition to the existence of an individual, a relation of an organism with itself, and the origin of "concern" based on its ongoing self-produced identity. One could envisage the circularity metabolism-membrane entirely from the outside (this is what most biochemists do) (Weber & Varela 2002 116).

Not only chemists — I propose the view of autopoietic-extended design is one from the "outside" and sanctioned in the above by Weber and Varela (2002) and Clark (2008a. b). Furthermore, Weber and Varela allot individual purpose to the recursive duty of "'concern' based on its [teleology's] ongoing self-produced identity." Teleology, drive, or sense-making in the above context, recognizes cognitive agency provisioning autopoietic adaptivity in order to help organize and construct animal-built structures as extended phenotypes (Clark 2001b. Dawkins 1982. Di Paolo 2010. Turner 2010).

Thereafter, activating the parity principle, I read Clark's (2008b loc 382) "environmental engineering is self-engineering" as recursive feedback not only in tune with extended phenotypes as described by Hansell (2005 194) but also with Weber and Varela's autopoietic "ongoing self-produced identity" (2002 116). The buttress of self-engineering, self-maintenance, and self-produced identity thus finds in autopoietic-extended design, biological

mechanics similar to those referred to by Clark (2008a xxv) involving Feynman's *thinking on paper* in the realm of extended phenotypes (Clark 1997. Dawkins 1982. Hansell 2005. Turner 2000).

In *Being There*, Clark cites examples of species-to-environment extended cognition (Clark 1997). Notably he moves beyond standard portrayals of extended phenotypes (Clark 2001b. Dawkins 1982. Hansell 2005). He considers animal-built structures such as the cricket burrows as — environment-to-cognition-to-environment — relationships requiring agency, perceptual monitoring, two-way communication, and maintenance. While clearly not considered causally or distinguished as maintenance by the cricket, the chores are likely to be genetically mapped (Weber *et al.* 2013), and physiologically responsive (tuned performative) acts involving built structures responding to the environment (Clark 2008a. Clarke *et al.* 2013. Coyne 2010. Turner 2000).

Extended phenotypes mapped to two genes were recently documented and discussed in *Nature* (Weber *et al.* 2013) as expressing unambiguous attributes of animal architectures. The *Nature* editorial noted:

Weber and colleagues show that the sophisticated burrows of oldfield mice can be understood using straight forward genetics, shedding light on how this classic 'extended phenotype' evolved" (Goymer 2013 312).

That does not mean mechanisms of extended cognition will also be traced to individual human genes activated or active in extended phenotypes — but it does activate questions. Nor, is a genetic breakthrough for extended cognition essential to establish coupling-parity between extended phenotypes and extended cognition mechanisms. While specific attributes of mouse burrows have now been sequenced to genes and performance verified in laboratory experiments (Chapter 2. 2.3) conducted by Hopi E. Hoekstra, Jessie N. Weber, and Brant K. Paterson (Weber *et al.* 2013), the research is still a long way from documenting human equivalents.

Nevertheless, the connection of genes to extended phenotypes and animal architecture (Goymer 2013. Weber *et al.* 2013) begins to relate genes to building (burrow construction) with implications not only for computational architecture but also for biologically generative architecture. Weber *et al.*'s experiments document the autopoietic unity of *organism* (mouse) + *cognition* (the mouse's genetic building program) + *environment* as they come together in the construction of an extended phenotype. Weber *et al.* note:

Animal architectures, such as beehives, bird nests, spider webs, termite mounds and rodent burrows, are remarkably diverse traits that can evolve through natural selection. Despite their great diversity, these extended phenotypes have similarities: they seem to be constructed through largely unlearned motor patterns; they are often consistent within a species (or population); and, when architectures differ, these differences reflect important fitness-related functions in the wild. Thus, genetic changes are predicted to contribute to the evolution of different architectures, even between closely related species (Weber *et al.* 2013).

Since genetic expressions manifested as physical forms — dependent on "distinct behaviors" — may be considered extended phenotypes realized by living systems, animal architectures appear to be genetic expressions (Dawkins 1982. Hansell 2005. Odling-Smee 1992. Odling-Smee *et al.* 2013. Turner 2000. Weber *et al.* 2013). As extended phenotypes, they answer with biological logic to explanations for constructions that are frequently labeled living architecture. But they are not, in my experience, cited as explanations paralleling human tool, technology, or structure usage — what Le Corbusier (2007 89) called the "house-tool" (Bennet-Clark 1987. Dawkins 1982. Malafouris & Renfrew 2010. Turner 2000. Webb 1996. 2009).

Extended phenotypic architectures are frequently constructed according to biologically inherited traits witnessed in animal behavior resulting in structures and earth works. Nevertheless, nothing in theory prevents extended phenotypic architectures from explaining human buildings masked under layers of technology, cultural ignorance, toxic pollution, and/or industrial production (Odling-Smee 1992. Odling-Smee *et al.* 2013).

By comparison with human architecture, extended phenotypic structural maintenance by other animals exhibits elements of adaptation and sense-making in areas where, for example a spider repairing her web exhibits monitoring and surveying skills for dealing with unforeseen events and damage in a species-built object. Active species surveillance, prediction/anticipation, and emergency response then indicates a characteristic of living systems and a degree of commonality among species in spatial (niche) occupation and maintenance that integrates extended phenotypes, extended cognition, and evolutionary, environmental survival strategies (Clark 2013. Dawkins 1982. Hansell 2005. Di Paolo 2005. Odling-Smee *et al.* 2013. Turner 2000. Weber *et al.* 2013).

Compare a cricket constructing a singing burrow to a bowerbird (*National Geographic* 2010) constructing a ritualistic, aesthetic display (Bennet-Clark 1987. Hansell 2005. Turner 2000). Both species are engaged in extended cognitive loops where adaptation must be factored into the motivation that produces the crickets and bowerbirds aesthetic product. The creatures'

actions demonstrate expectation, anticipation, and choice; they work toward results and modify constituent components as necessary to reach goals manifested in physical forms or displays. Hansell discusses aesthetics, structure, and design and bowerbirds figure in his work:

To propose that an animal has an aesthetic sense is to claim that it obtains some satisfaction or pleasure from an experience. Darwin (1871) [*The Descent of Man*] made this clear, when expressing his view that bowerbirds did assess conspecific displays in this way (Hansell 2005 158).

If we pair intrinsic teleology with sense-making, these acts of making, generating, and modifying may sometimes be logged as goal-driven behavior (Di Paolo 2002. Maturana & Varela 1980. Weber & Varela 2005). Such directed objectives are aimed toward positive responses for ultimate reproduction in constructing a sound amplifier or making an aesthetic display (Turner 2000). Crickets and bowerbirds illustrate purposive biological cognition and intelligence — *cognition-to-environment* as well as *environment-to-cognition* — where, for example the cricket and his burrow are not merely relegated to passive shelter/instrument building, nor is the male bowerbird behaving idiosyncratically; rather, they are both cognitively engaged with their environments for a biologically driven purpose that also involves cognitive-artistic judgment and options (Hansell 2005). Those built environments are then purposively connected to anticipated (genetic, cognitive) results. In both examples there are elements of complexity-driven, ground-up, subjective choices, aesthetics, and materials performance.

The architectural function of tuning (Coyne 2010) and amplifying the cricket's mating song is easy to comprehend as being tied to reproduction of the species (Turner 2000). But if the female cricket, or the female bowerbird, makes an aesthetic choice based on the burrow's tuned sound, or the male bird's arranged/organized display, their discrimination indicates cognitively engaged choice. Cognitively sourced display then aligns with both a variation of Clark's parity principle and autopoietic coupling (coupling-parity). Bird and cricket performances in the environment are signals awaiting a reply. Were cricket or bird performance, made or enacted by our own species, such engagement would be ascribed to aesthetic, cognitive discrimination involving choices based both inside and outside the head (Bennet-Clark 1987. Clark 1997. 2001. 2005. 2008a. Hansell 2005. Maturana & Clark 1980).

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7.5 • An Autopoietic-Extended Design Exercise

Characteristics of agency expressed in acts of recognition, identification, and distinction give heft to Di Paolo's program for *adaptive autopoiesis* in his papers "Extended Life" (2008) and

"Robotics Inspired in the Organism" (2010). Di Paolo's contributions to autopoiesis account for functions dependent on metabolic homeostasis that, when selected for sense-making or purposive goals (like those needed to achieve design performance), include differing categories of life intelligence — for example, between sponges, bacteria, and higher animals. Activated in a hybrid relationship with extended cognition, autopoietic definitions of minimal life support identifying autonomous sense-making enacted in extended phenotypes collaboratively constructed between agents and environments: the nest mediating between bird and environment; the house mediating humans and environment (Hansell 2005. Turner 2000). Sense-making and intelligence in autopoietic-extended design then literally interfaces life, technology, matter, and environment while still prompting us to acknowledge Turing's (1952. 1953) influence from morphogenetic and machine intelligence research (Chapter 5). Furthermore, design sense-making and intelligence participate in research typified where:

... robots are currently perceived as ideal candidates for the next electronic revolution, mastering the implementation of even relatively simple levels of "intelligence" would not simply boost the performance of current artifacts [buildings]. It would rather launch a broad technological revolution (Montebelli *et al.* 2013 300).

Beyond robotics the implications from Montebelli *et al.* are for *metabolic* objects and environments that if framed for architectural research, might be projected to underwrite metabolic generative design similar to:

... a biomechatronic hybrid endowed with a simple artificial metabolic system ... [where an] on-board living bacterial population processes biomass, providing the robot [building] with the electrical energy needed for sensing and action. ... [D]iscussion will highlight the cognitive implications that might be relevant to the development of a sound cognitive living technology, that is, engineered systems whose power specifically derives from core properties of the living system (Montebelli *et al.* 2013 301).

One response to Montebelli's "implications" for autopoietic-extended design stresses the need for design learning to enhance biotechnological recognition of natural systems and abilities in order to study metabolic systems for building performance (Armstrong 2012. Bedau *et al.* 2010. 2013. Cronin 2011. Di Paolo 2010. Montebelli *et al.* 2013). Along similar lines, Di Paolo comes close in "Extended Life" (2008) to proposing conditions, as I do for different ends, for a collective relationship with Clark's extended cognition. Here I intend those ends to deploy

autopoietic systems as working guidelines for generative metabolic design (Clark 2001b. 2005. 2008a. 2010a. Clark & Chalmers 1998. Di Paolo 2008. 2010. Maturana & Varela 1980).

Clark's research interfaces cognition and environment, and along with Di Paolo's "Organismically-Inspired Robots" (2003), complements Montebelli *et al's* (2013) biorobotic research. Di Paolo seems to suggest a convergence in "Extended Life" (2008) of autopoiesis (in the guise of enactivism) and extended mind (EM). After an analysis of Clark's work, Di Paolo (2008 20) articulates autopoietic adaptation and sense-making:

We can list some of the contributions of the enactive approach to the EM [extended cognition] story. . . . [T]he richness of environments as active media has so far been underplayed in the current enactive story. EM has sought to thematize this richness and the enactivist should listen (Di Paolo 2008 20).

Autopoietic-extended design has listened, resulting in hybridized extended mind for environmental input continuous with autopoiesis and biodesign implementation (Gibson 1986. Jonas 1966). From resulting research visualizations, I expect students will retrieve data differing from those in existing learning systems. The example I propose, and have discussed with Clark in relation to extended cognition (Peter's Yard. 1pm. 10/02/13), morphologically and phenomenologically explores and extracts design data from botanic performance. The system thus targets nature, via directed observation with technological enhancements, to channel insight/input for students to convert as design output.

Specific to our discussion, was a winged *acer* seedpod easily found on Edinburgh's streets and parks and similar to the *Tipuana tipu* seedpods I find in Barcelona and use in graphic depictions here (Fig 29, p278). Sitting in Peter's Yard (Edinburgh) over coffee, I tossed the seedpod in the air and we watched its mono-blade, helicopterlike flight. Observing the flight trajectory with particular attention to its helicoidal path, Clark and I discussed the seedpod's performance in terms of observational data we could witness and trace or document in photographs or video. Yet there was neither a physical trace of the performance, nor a hint of it outside of the seedpod's morphology.

What Clark and I witnessed was in-flight spiraling phenotypic actions (biologically enacted by the organism) inscribing invisible trails of phenomenological data available to students and researchers only deductively or technologically. This phenomenological spiraling trail is a type of data autopoietic-extended design specializes in identifying by aiding students in recognizing and visualizing force-field performance in nature for ideas and then design. In a sense, the flight of the seedpod is a gestural extended phenotype, still consistent with



Fig 29. Seedpod Data & Morphology. Page from the Student Handbook (Appendix 1). Flight of the seedpod is dependent on wind and moisture giving each flight a different data profile, frequency, and duration; here used as data input for biogenerative, morphological factors in the design of the three-spiral, flexing structure for the above footbridge. Xfrog/Rhino/3DS Max. Design: Dennis Dollens and Ignasi Pérez Arnal. Drawings and renderings: Dennis Dollens.



Fig 30. Mobile Video, Distribution & App Production. Page from the Student Handbook (Appendix 1). The flower stalk of the yucca (*Yucca glauca*) was used for phyllotaxic pod distribution and spacing to generate the PodTower model in the background. The flowers spiraling around the stalk are morphologically representative of the same type of data Turing depicted in his drawings involving phyllotaxis and parastichy (Figs 24-25, pp188-189). Xfrog/Rhino/3DS Max. Drawings and renderings: Dennis Dollens.

Hansell (2005) and Dawkins (1982) in the flight's purpose to "alter the fitness of the organism responsible for them" (Hansell 2005 194). In this case, the fitness action would be delivering the seed out of the shade of the parent to enhance chances of germination.

Performance data of this nature, available for design inspiration and interpretation, was illustrated by the seedpod's flight as well as its immaterial data trail. Clark and I discussed this phenomenological data as perceptually understandable through cognitive extension registering data useful for 2D and 3D design. Witnessing and documenting the phenomenological display is one mode for visually and technologically intercepting and interpreting data from the morphology of the seedpod and its flight. Observation and documentation are clear and basic examples of bio-investigative research methods that students may implement with technology focused on natural elements, forms, and phenomena (Figs 1, p29. 2, p44. 3, p45. 11, p93. 29, p278. 30, p279 & Appendix 1). The seedpod example then serves as a prototype for data extrapolation from nature at various levels of class, method, and research assignments.

The flight path as data-to-information (Fig 29, p278) is then a schematic exercise defining how environmental investigations can be used for studio or m-learning assignments interpreting biological form and action as data from nature for informing architectural systems. The exercise is one of several illustrated demonstrations gathered in the Student Handbook (Appendix 1). They all involve examination of matter, phenomena, and purpose in ways that can be decoded as design-harvested data from an in-field, technologically aided learning experience. As a learning example, the seedpod demonstration situates students as investigators of living and phenomenological data collaboratively collected through site occupation and powerful technology (Hensel 2012. Spiller 2009. Thompson 1992. Weinstock 2006a b).

To point: the shape and surface area of the winged seedpod determines its aerodynamic rotational pattern relative to the prevailing wind, weather, and the counterweight position of the seed itself. The flight creates data whose pattern may be documented as natural performance from which information is gathered and/or constructed for biomimetic design transformations similar to those we saw earlier in Clark's (2003 143) comparison of a slug's trail to Amazon's shopper data (Chapter 7. 7.2).

Easily reproducible, the seedpod demonstration for autopoietic-extended design may be coordinated with drawing apps, social media, and digital objectives and applied at various scales and levels of complexity. Students conduct assignments in the manner of DIY research in order to extrapolate types of biological or metabolic performance data appropriate to their individual projects (for example, in slow motion video capture, or analysis with a microscope). In a broad view, taking data from a seed, leaf, shell, bone, or flower forefronts Turing's suggestion (Chapter

5. 5.1) that intelligence may be considered in a spectrum broader than the measure of human cognition (Turing 1950).

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7.6 • Gaming: Go There, Do This, Get That

With machines defined as components brought together to achieve a goal, a similar consideration of architectural components tied to goals — shelter, monitoring, sensing, or playing involving metabolism — constitute a machinic phylum in which architecture may cross into biological territory (Chapters 1. 1.3 & 5. 5.2). In this grouping, life and matter are collaborative and hybridized, so consideration of *architecture as machine* potentially teams with metabolic domains and extended environments. Already discussed (Chapter 6. 6.1), Chris Gosden's, "The house is an intelligent object" is one conceptualization of metabolic architecture within autopoietic-extended cognition (Gosden 2010 41). To elaborate, I emphasize Clark and Chalmers's brief but critical question at the junctures of cognitive and physical environments:

... where does the mind stop and the rest of the world begin? (Clark & Chalmers 1998).

Toward an answer, they stress:

... the biological brain has in fact evolved and matured in ways which factor in the reliable presence of a manipulable external environment (Clark & Chalmers 1998).

And:

... the brain develops in a way that complements the external structures, and learns to play its role in a unified, densely coupled system. Once we recognize the crucial role of the environment in constraining the evolution and development of cognition, we see that extended cognition is a core cognitive process, not an add-on extra (Clark & Chalmers 1998).

Robert Wilson offers a variation:

One way to express the extended mind thesis is to say that, for at least a variety of cognitive activities, the physical configuration for the brain is not metaphysically sufficient for their performance *qua* cognitive activities. Something more is needed, and

that something more involves the physical configuration of the world beyond the head (Wilson 2010 179).

In relation to “something more is needed,” comes objects-of-experience from Mark Rowlands:

Most, if not all, recent treatments of experience presuppose — sometimes implicitly but usually explicitly — that experiences are *objects* of some sort. . . . I mean that they conceive of experiences as items of which we are, or can be, aware (Rowlands 2010 274).

Rowlands qualifies and expands this thought, bringing *objects* in range, then positing:

Let us call this the *empirical* conception of experience. . . . To say that an item [of experience] is empirical is simply to claim that it is an actual or potential object of consciousness, it is the sort of thing of which I might become aware if my awareness is suitably engaged (Rowlands 2010 274).

Subsequently he lists three examples where *objectness* engages cognition “between a subject and her experiences” to determine experiential processes:

- 1) Experiences and what it is like to have them are objects of *knowledge*.
 - 2) Experiences and what it is like to have them are objects of *introspection*.
 - 3) Experiences and what it is like to have them are items to which we have *access*
- (Rowlands 2010 275 original emphasis).

The three points help conceptualize sensory and cognitive processes for organizing autopoietic-extended design between phenomenological objects and thinking as co-existent with physical objects in nature. Rowlands’s construction of input is compatible with memory-retrieved-through-objects and/or objects-of-thought generation supporting ideas gained by experience. In this sense, architecture and design are cognitive processes and therefore inseparable from nature. Secondly, experiences may be enhanced through technologically accessed data augmenting what Rowlands (2010 275) cites as *knowledge*, *introspection*, and *access*.

The experiential subjective then encounters the physical world and pliable matter in discourse and that interchange results in both phenomenological input and output touching

design production (Guattari 1995). Rowland's breakdown of experiences unfolding into knowledge and introspection frames an ontology for the way *things* in the environment interact with cognitive processes to create what in autopoiesis is termed unities (Maturana & Varela 1980 77); these unities exist in relation to constructive, or constructed student, designer, and researcher subjectivity.

Consequently, the autopoietic-extended design endgame is experientially cognitive and observational — it helps generate ideas manifested from nature and technology into designed physical objects (extended phenotypes) embedding properties from which students construct knowledge used to construct architecture. In this recursive conceptualization, objects and materials embed and communicate design potential, phase-changes, and environmental action while also engaging memory and thought generation for perceptual data decoding, potentially hybridized for performative building design. The articulation of nurtured design ideas as design research then enacts Di Paolo's (2002) intention for autopoietic sense-making *experienced* as place and material making.

The autopoietic-extended design OS helps conceptually frame, organize, and access experienced input for constructing the design process, making or causing the fabrication of objects as cognitively extended output returned to the environment as biophysical, experiential architecture. The process is illustrated in the example we viewed of data extrapolated from the flight of a seedpod returned to the environment as a pedestrian footbridge (Fig 29, p278); other examples in the Student Handbook track different results from similar procedures (Fig 30, p279. and Appendix 1). From within the OS, I thus register programmatic relationships between "objects-of-introspection" creating objects-of-design and data flows to justify autopoietic-extended design scaffolding and methods (Clark 2008a. Gibson 1986. Rowlands 2010). That scaffold supports the unity of *student + cognition + technology + nature* collaboratively designing in an autopoietic, metabolic domain.

A product, object, machine, or building designed through the above process closes the cognition-to-object loop when nurtured in the world of student/designer's intention, the form's function, and its material's tactile, intelligent, and perceptual data (Chapter 4). In 1918 Sullivan pronounced:

... a building should live with intense, if quiescent, life, because it is sprung from the life of its architect (Sullivan 1979 184).

Today we find in extended cognition methodological recognition of what may seem purely transcendental sentimentalism in Sullivan's writings (Menocal 1981. Paul 1962. Sullivan 1896.

1979. 1999. 2009). Through versions of autopoietic-extended design, we may now cultivate theoretical and biological support to analyze embedded, embodied, and extended properties of life and mind as attributes of designed, made things (Clark 2008a. Di Paolo 2005. 2008. Menary 2010. Thompson 2007. Weber & Varela 2002).

Rowlands's above discussion of cognitive objects and experience applies to autopoiesis and extended cognition's role in the generation of ideas for design and learning. His trail of "knowledge," "introspection," and "access" (Rowlands 2010 275) signpost ways that experience may be pedagogically mapped for learning related to digital strategy frequently used in videogames outlined earlier as: *go there, do this, get that* (Chapter 1. 1.7). As machinic coded rules — *go there, do this, get that* — considered in terms of learning strategy vis-à-vis smartphones and procedural game-influenced methods (Gee 2007. Kirkpatrick 2011. Whitton 2010) helps engage epistemic actions (Johannsen 2010 61) and expectations for tangible research/design results.

Here I initiate the rule-base, *go there, do this, get that*, in order to contextualize in-field autopoietic-extended design as educationally generative of gamelike risk and its subsequent challenge to education (Bayne 2008. Fenwick *et al.* 2011). The experience of smartphone/app space for e- and m-learning, partly analyzed through videogame-related quests rather than as texts or lectures, then has practical lessons for distance and mobile design learning (Galloway 2006. Kirkpatrick 2011. Pew Internet 2013. Wark 2007).

This digital territory pioneered by smartphones, apps, videogames, and social media I consider for m-learning environments where metaphors of videogame traps, dragons, and monsters must be overcome to construct the treasure of knowledge/insight. If we translate traps, dragons, and monsters into learning challenges, and treasure into knowledge, a view of learning processes mirrors skeletal gamespace tactics useful to virtual teaching and learning (Gee 2007). In this context I hear, "The Future of Gamification" forecasts that by 2020 "there will have been significant advances in the adaptation and use of gamification. It will be making waves on the communications scene and will have been implemented in many ways for education" (Pew Internet 2013).

William Gibson, in a talk at Book Expo 2010, made a strong observation I place in relation to autopoiesis, extended cognition, mobilephones/apps, and gamespace supporting smartphone-mediated pedagogy. Gibson, speaking of age demographics, referenced ontological futures interfacing past memory and future conjecture. He concluded that anyone old enough to write a postgraduate dissertation already occupied a different world from that of upcoming undergraduates.

If you're fifteen or so, today, I suspect that you inhabit a sort of endless digital Now, a state of atemporality enabled by our increasingly efficient communal prosthetic memory (Gibson 2010).

In Clark's 2003 book *Natural Born Cyborgs*, I detected a compatible *digital now* mindset continually evolved through *Supersizing the Mind* (Clark 2008a) and his YouTube lecture, "Perceiving as Predicting" (2013). Compared to which, Gibson's (2010) "increasingly efficient communal prosthetic memory" paints growing alarm for out-of-sync pedagogical design-learning narratives.

Theoretical catch-up and the understanding of intelligences through computation, alternative biologies, or plant neurology (Brenner *et al.* 2006. Pollan 2013) are components of what I think architectural education, in relation to biological environmental performance needs to consider and then devise how to teach. Recently Neil Gershenfeld talked about MIT fablabs going global in two *Foreign Affairs* articles; he noted biological fabrication as part of the fablab revolution (Gershenfeld 2012. Gershenfeld & Vasseur 2014). Even more recently the online tech blog, *Engadget* reviewed biological 3D organ printing (Moon 2014) and Anthony Atala demonstrated organ printing in his TED talk (Atala 2011).

With components of life potentially emerging as 3D-printed objects capable of participating in life, I feel pressure to redefine design fablabs and in-class discussion of architectural biodesign — to challenge students' thinking regarding synthetic-life fabrication and the approaching use of living technology (Bedau *et al.* 2010). Generative architecture, in order to occupy the *digital now* and to engage nature, metabolism, and objects calls for protocols to guide student approaches to learning beyond traditional studios (Armstrong 2012. Bayne 2010. Fenwick *et al.* 2011). Autopoietic-extended design hereby provides theoretical orientation ready to support exploration of scientific and technological breakthroughs, synthetic biology, and conceptualizations of metabolic bioremediation as part of thinking and learning about generative architecture.

One potential for engaging the *digital now* is to activate experimental protocols linking computation, biology, and environments to experiential research. How do we move from the everyday use of technology to an engagement incorporating nature that translates into relevant research and fabrication for autonomous ecological architectural performance? Katherine Hayles makes a strong case for understanding systems and autopoiesis outside of biology by proposing that narrative be categorized as a technology (Hayles 2012). She points out that Maturana's theory is corrupted by narrative:

Even when he is concerned with the linear branching structures of evolution he turns this linearity into a circle and tries to invest it with a sense of inevitability. Narrative is encapsulated within the system, like a fly within amber. Seen as a technology, *The Tree of Knowledge* [here: autopoietic-extended design] is an engine of knowledge production that vaporizes contingency by continuously circulating within the space of its interlocking assumptions (Hayles 2000 156).

I relate autopoietic-extended design to: "an engine of knowledge production" and take Hayles's point that narrative has, from the beginning, been a driving autopoietic force. Therefore, the hybridized OS scaffolding I place narrative in, is not phenomenologically foreign to an experiential design process, videogames, social media, city street, or the *digital now*. Learning, in Hayles's frame of autopoietic narrative then hovers in emergent narratives students activate via the autopoietic-extended design OS. Their engagement with nature via technology to secure input data for design extrapolation is part of autopoietic-extended design's strategy. That strategy, implemented by autopoietic-extended cognition, is ultimately a narrative construction of reality (Hayles 2000. Lettvin *et al.* 1959). Reflecting back on earlier discussion of autopoiesis, I reframe Maturana and Varela's (1980) bio-focused *narrative* (Hayles 2012) for a type of adaptation (Di Paolo 2005. Weber & Varela 2002) to ensure compatibility with Clark's extended cognition (Clark 2001b. 2003. 2008a. 2010b. 2013a) and Turing's vision of plant-to-algorithm computation, decoding, and simulation (Chapter 5).

By recalling that Weber and Varela's and Di Paolo's research concluded that autopoiesis required modifications for real-world application, I justify autopoietic adaptation (Di Paolo 2005. Weber & Varela 2002). Additionally, Clark (2013) has given notice in "Whatever Next? Predictive Brains, Situated Agents, and the Future of Cognitive Science," that he is evolving robust machinics to explain cognitive processes. Clark's new research strengthens environmental participation, prediction, and collaboration for cognitive processes that further illuminates design ontology situating architecture, as I have argued, as part of nature (Clark 2012. 2013. 2013a).

Thereby, the thesis adaptations now found in autopoietic-extended design — predisposed to technology, biological simulation, living technologies, and biogenerative systems — are significant for an architecture and learning methodology and research protocol that engages *student + technology + environment*. The OS scaffolding then helps to instruct, nurture, and guide students in the occupancy of a research site interpreted through Clark's philosophy

decoded as methods for constructing and designing in autopoietic domains for metabolically generative architecture.

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Chapter 8 • Conclusion

“Autopoietic-Extended Design” establishes a design and learning operating system for metabolic and generative architecture built upon extended cognition researched and theorized by Andy Clark. For balance, I elaborate extended cognition with supporting and contrasting views from cognitive science and philosophy (Clark 2008a. 2013a. Di Paolo 2005. Menary 2010. Noë 2009. Thompson 2007). Onto Clark’s theory I graft functions of autopoiesis (Maturana & Varela 1980) adapted for compatibility (De Paolo 2005. Weber & Varela 2002) with environments, organisms, objects, and extended phenotypes in order to synthesize architectural learning and research methods as continuous in nature (Dawkins 1982. Hansell 2005. Turner 2000). Evolved, operations from the above signal animate potential for biological agency and intelligence in buildings.

Schematically, autopoietic-extended design is biologically sensitized by autopoiesis and made operational via extended cognition (Clark 2008a. 2013b. Maturana and Varela 1980). Theory, from both autopoiesis and cognitive science, is translated into a design protocol, the OS, in which extended cognition contributes a formulation of mind-to-environment generative communication — autopoiesis (Chapter 3) contributes a biological prescription (involving components, unities, domains, structural coupling, and self-maintenance) for identifying minimal requirements of living systems. Together, they enable new design pedagogy (Chapter 6).

Through dialectic, the thesis posits autopoietic-extended design in association with advanced technology, biological simulation, synthetic biology, and AI in order to construct input/output from systems of intelligence, life, knowledge, machines, codes, objects, and nature as factors in metabolic and generative architecture (Clark 2001a b. 2003. 2005. 2007a b. 2008a b. 2010a b. Di Paolo 2005, 2008, 2010. Noë 2009. Menary 2010. Rowlands 2010. Thompson 2007. Turing 1950. 1952. 1953). When read as a dialectic nurturing questions, investigation, and synthesis autopoietic-extended design orients students toward constructive engagement with design experimentation. I thus construct a pedagogical scaffold — the autopoietic-extended design OS — to source intelligent, metabolic, algorithmic, and morphological data in order to hybridize and evolve theory, buildings, and architectural learning.

Pedagogically and theoretically, the OS overrides Cartesian binary divisions (Jonas 1966 102) enabling students to envision nature as a continuum (Gibson 1986 141). Binary divisions of mind/cognition, mind/body, and body/environment are reconfigured as seamless. I then situate built architecture first as constructs of mind and nature, and thereafter as constructs of matter, systems, and program — architecture as biointelligent machines in intelligent nature (Canguilhem 1992. Dawkins 1982. Hansell 2005. Nagel 2012. Turner 2000).

Nature, as an operationally closed system (pp71-72. p96), conceptualized and researched through autopoietic-extended design, harbors organisms suitable for architectural performative systems capable of being selected, adapted, or evolved for hybridizing intelligence in materials and infrastructures (Jonas 1966. Maturana & Varela 1980. Nagel 2012). That evolution sometimes generates physically realized structures and shelters. Those constructions — webs, burrows, shells, and buildings — cannot be decoupled from nature’s forces, phenomena, and matter; but they can be deciphered (Clark 2008a. 2013a. Di Paolo 2005. Hansell 2005. Maturana & Varela 1980. Turner 2000. Turing 1952. Weber & Varela 2002). The resulting decoding and interpreting — the cognitive and physical production/understanding of webs, burrows, shells, and buildings for example — draws upon the OS scaffold to dialectically alert students to processes for extrapolating data from nature. These processes are exemplified in Turing’s (1952) morphogenetic research (Chapter 5) and defined for architecture in Dawkins’s (1982), Hansell’s (2005), and Turner’s (2000) concepts detailing extended phenotypes I use as a primary classification to account and argue for the potential of metabolic architecture.

Consequently, the hybrid OS deploys dialectical oppositions by which debate or deliberation, plotted through the autopoietic unity of *student + technology + environment* supports students’ vision and their learnt construction of biogenerative morphological and metabolic design. The process attests to a driving protocol and nondualistic interchange that flows through nature, cognition, technology, and matter (Jonas 1966. Odling-Smee 1996. Turner 2000). That OS fluidity is programmatically activated when *student + technology + environment* function as an autopoietic unity engaged at a physical site to generate input/output in the currency of ideas and visualizations (Clark 2008a. De Paolo 2005. Maturana & Varela 1980. Weber & Varela 2002).

The physical research site in this organization thus becomes an exploratory microcosm, a laboratory of urban or wild nature facilitating experience, observation, and the capture of data. By technologically and phenomenologically sequestering and observing data, information is available to generate narrative, theory, and design ontologies (Luhmann 1990a). For example, narratives link design axioms such as *architecture = nature* to research definitions, protocols, and especially practice in linguistic strings like this:

environment + technology + student + data + theory = design precept

and/or

sense-making (bacterial cognition) + environment + object + theory = material precept

The protocol strings, configurable in infinite variation, become programming and organizational “agent-world circuits” (Clark 2007b) — schematic nodes (idea links) affected by complexity (Mason 2008. 2008a) to network and articulate design intentions. In a nodal state, the strings may be edited or programmed for linear and/or branching growth, sometimes interweaving attributes at which point a node becomes a multimodal data concatenation or terminates as a knot. In branching states, the nodes resemble tree structures similar to those used by Chomsky (1959) and those underpinning L-systems (Prusinkiewicz & Lindenmayer 1990). In biodigital design, for instance, branching L-systems (Chapter 5. 5.4) may be programmed as experimental, structural components (trusses, columns, beams) represented here in e-Trees (Fig 7, p78). I see these generative structures as reliant on theory and code established by Chomsky (1959), Maturana and Varela (1980), Clark (2008a), Turing (1936. 1952), and Lindenmayer. Lindenmayer (1968. 1971) confirms his links to Turing’s universal machines (1936) and below to Chomsky’s generative grammars:

... the Chomsky hierarchy of grammars ... provide us with an ordering of developmental generating systems and languages, giving us a measure of complexity in distinguishing primitive vs. advanced characters, whereas no such measure has been available before to biologists [or designers] (Lindenmayer 1971 456).

Moreover, Chomsky’s (1959) “On Certain Formal Properties of Grammars” referenced “unlimited [universal] Turing machines” as the (first of three) systems for linguistic generative grammars. Chomsky’s use of universal Turing machines five years after Turing’s 1954 death is pertinent to the lineage of biogenerative design. One sub-strain of which may be restated as the Turing > Chomsky > Lindenmayer lineage; Chomsky states (and I parenthetically insert autopoietic-extended design analogies):

A grammar can be regarded as a device [machine] that enumerates the sentence [structure] of a language [generative architecture]. We study a sequence of restrictions that limit grammars first to Turing machines ... (Chomsky 1959 137).

Lindenmayer (1968 205-206) later employed and acknowledged Turing’s (1952) reaction-diffusion differential equations (Prigogine & Nicolis 1967). His acknowledgement supports my conclusions in Chapter 5. Those conclusions see Turing (1952) founding computational biology (Reinitz 2012) and therefore a great-grandparent of biogenerative architecture — subsequently, and more efficiently coded by Lindenmayer (Chapter 5. 5.4). To

graphically depict a method of Xfrog's L-systems generation (Chapter 1. 1.6), I illustrate four towers from my own autopoietic, generative research (Figs 6-10a, pp76-89).

Nearly complete then, the scaffold for autopoietic-extended design reaches a point to contemplate release. Its programmable components originated in Clark's philosophy from which theoretical "larger hybrid wholes" (Clark 2007b 168) have been selected, integrated, and adapted with autopoiesis (De Paolo 2010. Maturana & Varela 1980. Weber & Varela 2002). These components autopoietically assist the recognition of metabolic organisms and mobilize their environments in an emergent epistemology of design. Echoing from earlier in the thesis, Weber & Varela's (2002 104) "man as a thinking subject is . . . part of nature" then includes designing as part of nature to animate ontological OS procedures instantiating technological (smartphone-enabled) learning. Designing as part of nature communicated between cognition, organisms, technology, and matter then follows, for one example, Clark's (2007a 265) depiction of the "biological-agent + stick" demonstrating *The Cognitive Life of Things* (Malafouris & Renfrew 2010) as integrated and environmentally coactive intelligence (Chapters 1. 2.0 & 6).

Clark's *agent/stick* unity expounds the workings of participatory environments in which object-to-cognition physically and phenomenologically routes data critical for realizing the design of extended phenotypelike constructions (Dawkins 1982. Hansell 2005. Turner 2000). Earlier, Clark wrote:

. . . [The] power and beauty of the brain's role is that it acts as a mediating factor in a variety of complex and iterated processes which continually loop between brain, body, and technological environment. And it is this larger system which solves . . . problem[s]. We thus confront the cognitive equivalent of Dawkins's (1982) vision of the extended phenotype (Clark 2001b 17).

Cognition-in-the-environment (Clark 2001b) as extendedly phenotypic, adapts and selects thought (see Rowlands, cognitive objects p277) addressed to the realms of tool-, machine-, burrow-, nest-, and building-making in ways that Hansell (2005) and Turner (2000) discuss as animal architectures (Chapter 7. 7.4). Designers thus confront theory articulating architectural thought/design as cognitive-state objects as well as visualizations and theoretical constructs preexisting formal architecture and bonding design cognition and metabolism in nature via agency, computation, and extended phenotypes (Dawkins 1982. Hansell 2005).

Accordingly, autopoietic self-maintenance with metabolic sense-making introduces natural attributes and properties that students may investigate to conceptualize emergent intelligent architectures (Appendices 1. 2). Theory, discussion, assignments, proposals, and

prototyping then nurture students' cognitive predictions (Clark 2013. 2013a) impacting design visualization striving to conceptualize metabolic, bioremediating architectures (Figs 1, p29. 2, p44. 3, p45. 11, p93. 29, p278. 30, p279). Herein, Clark's cognitive/environmental theory goes beyond metaphors of memory as deposited, contained, and/or prompted to track cognition-to-environment enaction (Clark 2001b. 2003. 2005. 2008a. 2010a). He hypothesizes cognition-to-object decoding between student agents and physical domains consisting of organism, phenomena, matter and force (Nagel 2012) pertinent to perceptions and prediction (Clark 2013. 2013a) from which students may address: *can buildings think?*

By organizing project data and by witnessing enactive living data, autopoietic-extended design suggests interfacing conceptual design, theory, observation, phenomenology, technology, and nature (Clark 2001b 17). It makes room for biorobotics and makes ready for synthetic biology and living technologies (Bedau *et al.* 2010). Hence, *affordances* as in perception of data (Gibson 1986) shadow Clark's mechanisms of cognition-to-nature communication. As Wells points out, Gibson's:

... affordances are ecological; they are facts of the environment and behavior; sets of them constitute niches; they are meanings; they are invariant combinations of variables; and they are perceived directly (Wells 2002 143. See also Odling-Smee 1996. Odling-Smee *et al.* 2013).

Gibson himself wrote:

The possibilities of the environment and the way of life of the animal go together inseparably. The environment constrains what the animal can do, and the concept of niche in ecology reflects this fact. Within limits, the human animal can alter the affordances of the environment but is still the creature of his or her situation (Gibson 1986 143).

"[P]ossibilities of the environment and the way of life" engage domains within autopoietic-extended design that activate the dialectical OS for exploring how to conceptualize autonomous, metabolic buildings (Armstrong 2012. Cronin 2011. Spiller 2009). Guattari, in his last book, characterized this realm with:

In such a case, institutions and technical machines [here, architecture] appear to be allopoietic, but when one considers them in the context of the machinic assemblages

they constitute with human beings, they become ipso facto autopoietic. Thus we will view autopoiesis from the perspective of the ontogenesis and phylogenesis proper to a mechanosphere [domain in autopoiesis] superposed on the biosphere (Guattari 1995 40).

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The autopoietic-extended design context of theory, technology, biology, observation, and agency sets up two dialectical stages where:

Stage 1) Establishes a process for identifying and then translating metabolic and intelligent functions from nature in order to replicate desirable natural traits as elements of generative computational-to-bioperformative architecture. At this stage, decisions are made concerning how, and in what configuration, AI (Langton 1988), synthetic biology (Garrett 2013. Venter 2013) and/or living technology (Bedau *et al.* 2010. 2013) will be introduced into research.

Stage 2) Positions generative architecture in a research/education context (Chapter 6) that coheres around autopoiesis, extended cognition, digital systems, emerging science, and metabolic systems variously related through Sullivan's (1999) morphological drawings and *System* (Chapter 4), and Turing's (1952. 1953) morphogenetic drawings, digital simulations, and computational programming (Chapter 5). This lineage is then foundational for ideas/processes that serve to extrapolate attributes, which in turn update form finding in morphological, botanic, and embryological observations necessary to generate or prototype intelligent architecture.

To interface stages 1 and 2 is an exercise in excavating biological theory (Maturana & Varela 1980), cognitive science (Clark 2008a), and holdings in autopoietic-extended design's *machinic phylum* (p58) for orienting research toward morphological, metabolic, and synthetic biologies. In this scenario architecture is argued (Chapter 7. 7.4) as a human extended phenotype (Dawkins 1982. Hansell 2005. Turner 2000), with the understanding that technology represented, for example, by synthetic biology (Garrett 2013. Venter 2013. Weber *et al.* 2013.) is rapidly approaching a point at which extending architecture by means of animate, sense-making organisms will be possible (Bedau *et al.* 2010).

Investigations of living technology, for another example, establish typologies of metabolism and intelligence transferrable to autopoietic architectural domains where extended phenotypic components may be decoded from nature — reconceptualized and reconfigured —

and then grafted into sense-making infrastructural and material systems (Armstrong 2012. Clark 2008b loc 2597. Cronin 2011. Spiller 2009. Spiller & Armstrong 2011. Weber *et al.* 2013). By reconceptualizing and reconfiguring architecture in nature through autopoietic-extended design, students are encouraged (Chapter 6) to inhabit and experience their research sites in relation to matter/organisms while simultaneously interfacing their research with relevant data from technology and science (Armstrong 2012. Garrett 2013).

With the legacy of Turing's (1952. 1953) biocomputational and embryological simulations and his hand rendered drawings factored in (Figs 24-28, pp188-192), autopoiesis and extended cognition brace the OS as "wholly inconsistent with dualism in any form, either mind-matter dualisms or mind-body dualisms" (Gibson 1986 141). Considered in an environmental continuum, biogenerative architecture becomes a process banishing dualistic inconsistencies in order to clear the divisive mind/matter distinction that severs human cognition from nature and, by extension, architecture from nature. To these ends, Nagel (sounding like Sullivan, Chapter 4) argues for a synthesis of mind/matter/nature that recognizes mind/cognition as a force of nature. He encapsulates principles essential to nondualistic autopoietic-extended design:

Everything, living or not, is constituted from elements having a nature that is both physical and nonphysical — that is, capable of combining into mental wholes (Nagel 2012 57 loc 732).

Field observation, morphological phenomena, metabolic systems, and form-finding data following on Nagel's quotation, give substance and first-hand experience to students/designers aided by smartphones, apps, and autopoietic-extended design. Requiring students to assemble in-field observational and morphological data is intended to establish a basis for experientially learning from metabolically intelligent and ecologically proactive research. Where Nagel's (2012) call for inclusion of mind as a force of nature holds sway, intelligent buildings hold potential as organisms (Chapter 1. 1.2). For metabolic architecture, Nagel's model implicates cognition-to-technology-to-environment as signal human teleological processes (p51) I use to validate theory necessary for envisioning autopoietic buildings as part of nature (Armstrong 2012. Dawkins 1982. Odling-Smee 1996. Turner 2000).

Building an autopoietic-extended design pedagogy — lessons, assignments, communication, research, and production — necessitates goals for expected learning or research (Bayne 2008. 2010. Fenwick *et al.* 2011). My redeployment of autopoiesis and extended cognition facilitates a series of piggybacking so that extended cognition, performing

more than its theoretical functions of cognitive-to-environmental networking, operationally supports recognition and communication as forms of nonconscious autopoietic sense-making and adaptivity (nonhuman intelligence for buildings) — what Di Paolo (2008 12) calls: "the normative engagement of a system with its world" (Di Paolo 2005. 2010. Maturana & Varela 1980. Nagel 2012. Weber & Varela 2002). The piggybacking (striation) of concepts promotes the objective of generating ideas from observation and experience — for example, routing attributes of plant neurobiology (Brenner *et al.* 2006), organisms, and/or plant simulations (Turing 1952. 1953. Weinstock 2006a) from biomechanical or biochemical life to biogenerative systems (Chapter 1. 1.5 p68).

Generative architecture as evolving here embraces phenomenological and metabolic functions nourished by observation (ocular and technological) as epistemological input/output. It facilitates unique cognitively derived interfacing of nature, organisms, and technology striving toward metabolic sensing as ontologically necessary for bioprocessing in buildings. In this formulation, prototyping metabolic architecture is compatible with existing studio software, programming, and machine 3D fabrication (Gershenfeld 2012) even as it awaits exposure to CNC biological (as in biological organ) fabrication and bioprinting (Atala 2011. Fountain 2013. Garrett 2013). Autopoietic-extended design thereby advances toward narrative articulation (Hayles 2012) engaging dialectical cross-examination of animate organisms and inorganic matter. The dialectic (anti-dualistic, extended phenotypic, autopoietic, cognitively inseparable from nature) posits emergent architecture and emergent learning as receptive to potential hybridization with metabolic intelligence and living technologies (Bedau *et al.* 2010. 2013).

Semantically, autopoietic-extended design situates Sullivan's morphological learning system (Chapter 4) and Turing's morphogenetic drawings and computational simulations (Chapter 5) in its *machinic phylum* (Chapter 2). That phylum, as a cell-like container of the OS, then hosts the equation:

"Can machines think?" = Can buildings think?

Posed in the Introduction and iterated through the thesis, the equation/question is syllogistically parallel when machines and architecture are speculated on as intelligent. And, while the syllogism below is highly qualified — pushing the boundaries of credulity — it has a job to do:

All neuromorphic Turing machines are intelligent.

All metabolic architectures are neuromorphic Turing machines.

Therefore all metabolic architectures are intelligent.

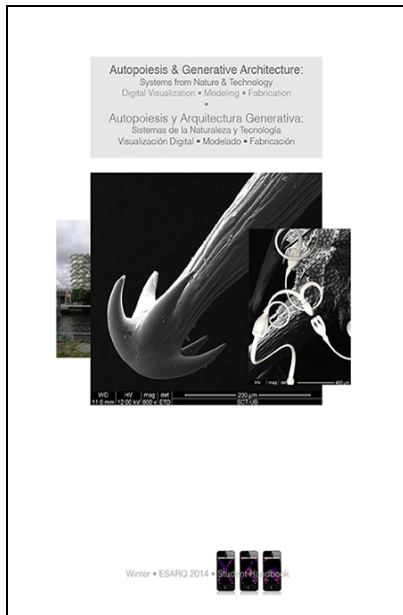
Notwithstanding hyperbole, the manipulative exercise serves to illustrate the conceptual point that autopoietic-extended design must overcome with each of its users: that machines and architecture may be constructed as metabolic and intelligent (Maturana & Varela 1980) in light of synthetic biologies, AI, and living technologies. Therefore, the syllogism (Corbett 1971) may be analogously remixed and hypothetically applied to a wide spectrum of devices, procedures, and constructions we now consider inanimate and unintelligent.

This lineage supports a design pedagogy hybridized from autopoiesis (Maturana & Clark 1980), extended cognition (Clark 2008a 2013), and computational simulation (Turing 1952. 1953). Activated as an OS for studio, e-, or m-learning (Appendices 1. 2), the hybrid enables design and research trajectories consistent with AI and biological intelligence as observed in the animal/plant/machine world (Brenner *et al.* 2006. Dawkins 1982. Hansell 2005. Turing 1936. 1952. Turner 2000). Those research trajectories then encounter cognitive, metabolic, and synthetic “life impulses” (Sullivan 1967 Plate 5 Fig 19. p161) intended to prompt student consideration of how buildings can be evolved toward bioremedial performance and thereafter as ecologically proactive.

Autopoietic-extended design, fast-forwarded as tool-, machine-, knowledge-, and building-making participates in phenomenological, material, and intelligent nature (Clark 2008. Maturana & Varela 1980). It sets up theory extended into pedagogical practice (Appendices 1. 2) through which research and observation methods seek debate, testing, extending, amending, developing, and distribution. The OS is now ready for beta release. It cognitively and methodologically extends the provenance of buildings, biology, simulation, technology, and theory viable through autopoietic-extended design research to conclude: Architecture = Nature.

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Appendix 1 •



Autopoiesis & Generative Architecture • Student Handbook • BioDigital Master Studio • Winter 2014
• Dennis Dollens, Tutor • ESARQ • Universitat Internacional de Catalunya

The 90 page PDF Student Handbook may be downloaded from Dropbox with the QR code or web address below. Five double-page spreads from this publication are illustrated in the thesis (Figs 1, p29. 2, p44. 3, p45. 11, p93. 29, p278. 30, p279).



<https://www.dropbox.com/s/5y0oy393kq57nr3/Thesis-ESARQ%20Handbook-14Aug2014.pdf>

Appendix 2 •

Twitter Manifesto: Autopoietic Architecture: Can Buildings Think?

IAAC • Spring 2014 • Dennis Dollens • (See Fig 5, p48)

Assignment

The seminar assignment consists of responding to weekly manifesto Tweets so that individual and group debate ensues. The idea is to generate a smartphone engaged studio dialectic given the economy of Twitter's 140 text characters, and to hijack social media into design theory and architectural discussion.

Theoretical, political, aesthetic, and technological considerations/ideas will emerge. Points of argument/discussion to consider are, for example: Can Buildings Think? and Can Buildings Metabolize? — Perhaps we imagine a new kind of architectural ALife or biorobotic building type? Subsequent points involve: nature and culture, digital and biological hybrids, robotics and synthetic life, AI and ALife.

Response-TWEETS need the hashtag #aupo (**autopoiesis**) for collection as a group statement. The seminar discussions and readings are theoretically keyed to the TWEETS. And the Tweets contain seeds for ideas growing potential algorithmic generation, design theory, botanic mathematics, new modes of bio-sustainability, simulation, and concepts for environmental remediation involving the role of an intelligent/metabolic architecture as responsive to environmental abuse and toxicity.

•

1. If nature produces life/thinking/ideas & they produce design; then architecture is part of nature. Tweet an argument. #aupo
2. Alan Turing proposed computational intelligence, asking: "Can machines think?" If **architecture = machine**, can buildings think? #aupo
3. Can buildings think? by default asks does: **architecture = nature**? Are bio-intelligent functions architecture's future? #aupo
4. If **architecture = nature** can a **building = life species**? Not conscious but responsive to environmental duty & sustainability. #aupo
5. Can the level of AI & sensor performance found in a smartphone be comparably applied to eco- & bio-performance in buildings? #aupo
6. Ideas are > phenomenological electromagnetic neuro-chemical forces; cognition includes nature's input for design idea-output. #aupo
7. Think of yourself in nature not its master; appropriate bio-performance in buildings modeled on biology & tech not fashion. #aupo
8. Concept: architecture & tech are extensions of human tool making, thought, & industry—therefore they're part of nature. Comment. #aupo
9. If a spider web is an extended phenotype, is a skyscraper or a house a human extended phenotype? What's an extended phenotype? #aupo
10. Is cognition's role in bioremediation, tech, & synthetic life linked to design via nature. Again, consider extended phenotypes. #aupo
11. W/ synthetic biology, robotics, ALife, & scripting, architecture has potential for intelligent & metabolic life. Tweet a scenario. #aupo
12. Le Corbusier's "A house is a machine for living in" today = "**a house is a living machine for living in**"—Tweet other variations. #aupo
13. Are smartphones machines for thinking—prosthetic data feeds w/ sensors & AI. What would bring them close to living machines? #aupo
14. Envision buildings as sustainable, proactive & working organisms. Ask: Can buildings live? What would a metabolic building do? #aupo

Appendix 3 •

Parts of this thesis have been presented at conferences and in journals.

Chapter 6 in an early and brief version appeared as "Alan Turing's Drawings, Autopoiesis, and Can Buildings Think?" *Leonardo Journal of the International Society for the Arts, Sciences and Technology*. The MIT Press. 47.3. 249-253. May-June 2014.

The Introduction was edited for presentation and publication in the conference proceedings: "The 2nd International Conference of Biodigital Architecture and Genetics." 4-6 June 2014. Universitat Internacional de Catalunya, Barcelona. In press.

"Autopoietic Architecture." Keynote Presentation. World Biomimetic Foundation. Barcelona. March 2014.

The "Urban Drift Student Handbook" from the July 2012 e-learning experiment hosted by the Moray House School of Education, University of Edinburgh, was presented at the Design ON e-Learning Conference as "BioDigital Design & Architecture e-Learning." London. 7 September 2013.

A general presentation on biomimetics and generative design: "Digital Biomimetics & Generative Architecture" was presented at the Roca Gallery: Barcelona. 21 May 2013. Paper, interview, lecture, and round-table discussion.

"Autopoietic Biodigital Design & Architecture." Journal publication. School of Design. University of Dammam. Saudi Arabia. November 2012.

Three papers are currently in process: one invited for the *Rutherford Journal* on Alan Turing's Morphogenetic Drawings and Generative Architecture; a second on autopoietic design learning methods and theory for *Studies in Material Thinking* (submitted 22 August 2014); and a third paper on autopoiesis and plant intelligence for *Communicative & Integrative Biology*.

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